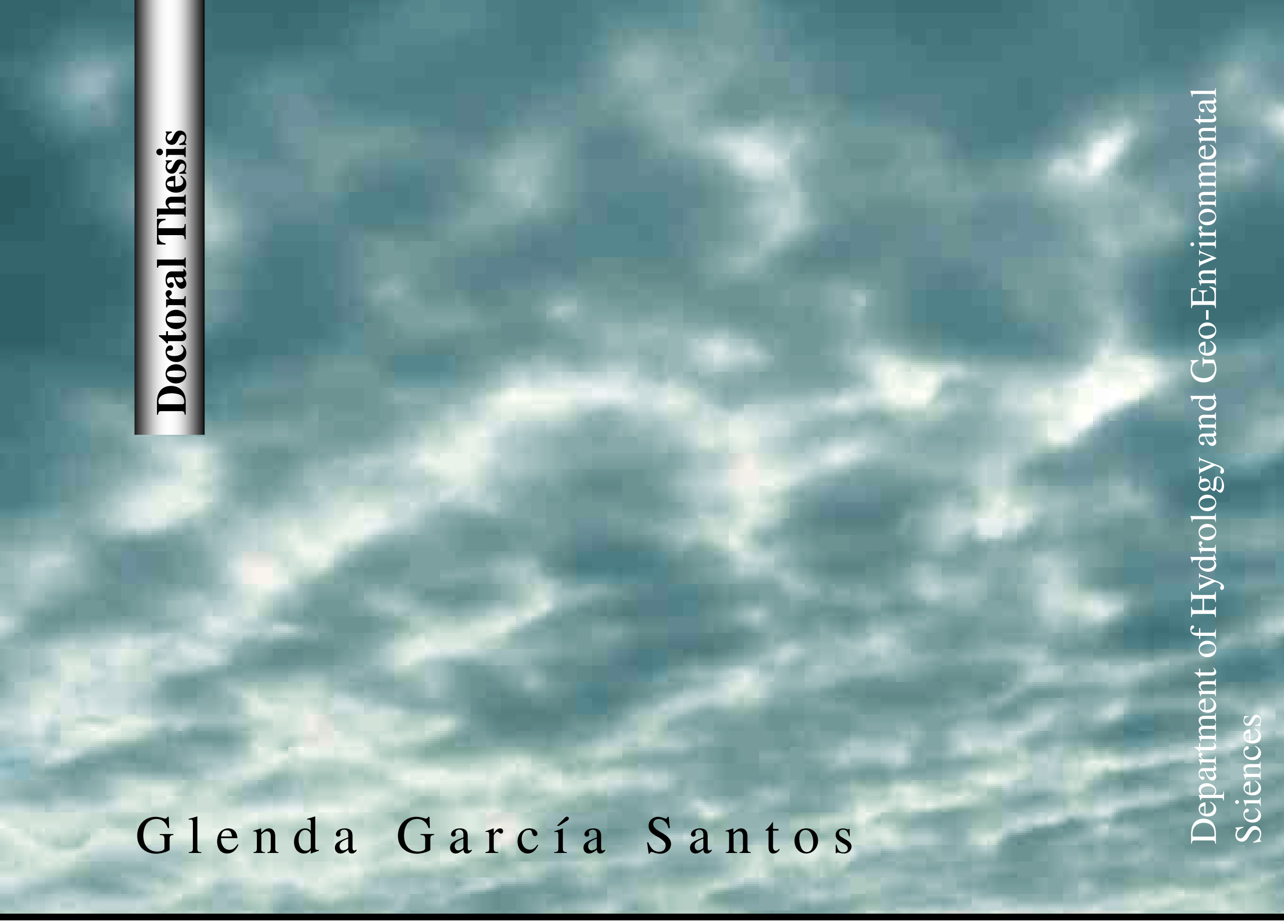

Doctoral Thesis

Glenda García Santos

Department of Hydrology and Geo-Environmental Sciences

An ecohydrological and soils study in a montane cloud forest in the National Park of Garajonay, La Gomera (Canary Islands, Spain)

Vrije Universiteit Amsterdam

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a mi Madre

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Chapter I

GENERAL INTRODUCTION

I GENERAL INTRODUCTION

I.1 BACKGROUND

During the Tertiary era a subtropical (cloud) forest type (*Laurisilva*) dominated by trees belonging to the family of the Lauraceae was widespread in Southern Europe (Braun-Blanquet, 1979). Today remnants of these forests occur only in the so-called Macaronesian region (i.e. the geographical group of central Atlantic Islands between 10°N and 40°N) which comprises the Cape Verde islands, the Azores, the Canary Isles and Madeira (Figure I.1). These laurel forests are typically located on slopes of northerly exposures at elevations between 800 and 1300 metres above sea-level where humid conditions prevail. The *Laurisilva* forest is important ecologically and botanically because due to its location within the generally dry subtropical region off the West coast of Africa and its own moist habitat it constitutes a link between the tropical moist forests of mainland Africa and the Mediterranean sclerophyllous forests further North.

In the Canary Islands, relic *Laurisilva* stands are mostly found on the western islands, with the centrally located island of La Gomera having the largest contiguous area of such forest (3,984 ha) forming the Garajonay National Park (Figure I.1). The Park became a UNESCO World Heritage Site in 1986 because it represents an “exceptional example of the biological evolution of the ecosystem of laurel woods, because of the international importance of its native flora (34 species), and because it is the last extensive example of an unusual ecosystem” (IUCN, 1987).

Natural green spaces in La Gomera are relevant not only because of their biodiversity but also from a water resources perspective. La Gomera has large dry, poorly vegetated areas (woodlands only represent 23% of the total surface area of the island; Consejería de Obras Públicas, (2003)), rough topography and poor soils, which, together with human disturbances implies a high risk of soil degradation and erosion. Today, 53% of the island’s wooded areas are protected through various environmental policies, and more than 38% is part of the National Park of Garajonay located in the centre of the island (Bramwell and Bramwell, 1974; Consejería de Obras Públicas, 2003). More than half of the surface of the National Park is covered by ‘*Monteverde*’ vegetation, the Spanish term used to denote evergreen montane vegetation in the region and referring to a variety of woodland types. These include laurel forest (covering approximately 11% of the island) located in the bottoms of the northern valleys where humid conditions are guaranteed throughout the year; and degraded *Laurisilva* found on wind-exposed peaks and ridges, where the native beech (*Myrica faya Ait.*) grows with heath trees (*Erica arborea L.*) to form a short-statured evergreen forest native to the Mediterranean and Macaronesian regions, in an association referred to as '*fayal-brezal*'.

The Canary Islands are situated on the south western edge of the Azores' anticyclone, and their coasts are subject to cold sea breezes from the surrounding Atlantic Ocean. This particular climatological setting combined with the presence of north-easterly trade winds and the rugged topography has resulted in the formation of a thermal inversion layer which manifests itself in the form of extensive stratocumulus clouds (often referred to as the "sea of clouds"). The clouds, to a lesser or greater extent, determine the occurrence of *Laurisilva* woodlands as they guarantee moderate temperatures and high relative humidity throughout the year, and mitigate the effect of the dry summer months. Indeed, Marzol et al. (1998) considered the persistently high relative humidity of the cloud belt as one of the main climatological determinants responsible for the maintenance of this vegetation.

The ecological importance of the Garajonay National Park has attracted a range of scientific studies, including investigations of its geographical and geological setting (Arozena, 1991), the climate, including the spatial and temporal occurrence of fog (Kämmer, 1974; Marzol et al., 1990; Santana, 1986), the vegetation (Bramwell and Bramwell, 1974; Golubic, 2001; Kämmer, 1974; Santana, 1990), as well as the chemical and physical characteristics of the soils (Arozena, 1991).

The need for continued and more detailed studies of the interactions between climate, vegetation and both surface and subsurface hydrological functioning in the *Laurisilva* zone of La Gomera has been recognized for some time now (Arozena, 1991; Consejería de Obras Públicas, 2003). However, such studies have their difficulties, primarily due to the lack of complete meteorological stations (Arozena, 1991), and the complex structure of the volcanic substrate which consists of a mixture of volcanic ashes, dykes and irregularly aggregated lava flows (Bravo and Bravo, 1990). Despite these limitations, headwater forest hydrological studies are essential to improve our knowledge of: (i) spatial and temporal patterns of rainfall and fog water inputs and their interception by the canopies of different forest types, (ii) soil water uptake patterns of the vegetation during wet and drought conditions, and (iii) amounts of water infiltrating and recharging soil- and groundwater reserves, or flowing off during torrential rains. Quantitative information on all of these hydrological fluxes as a function of forest type and elevation is of great interest, not only from the perspective of managing the Garajonay Park itself but also with respect to overall water resources management on the Island as demands for good quality water are on the increase and groundwater levels are falling (Consejería de Obras Públicas, 2003).

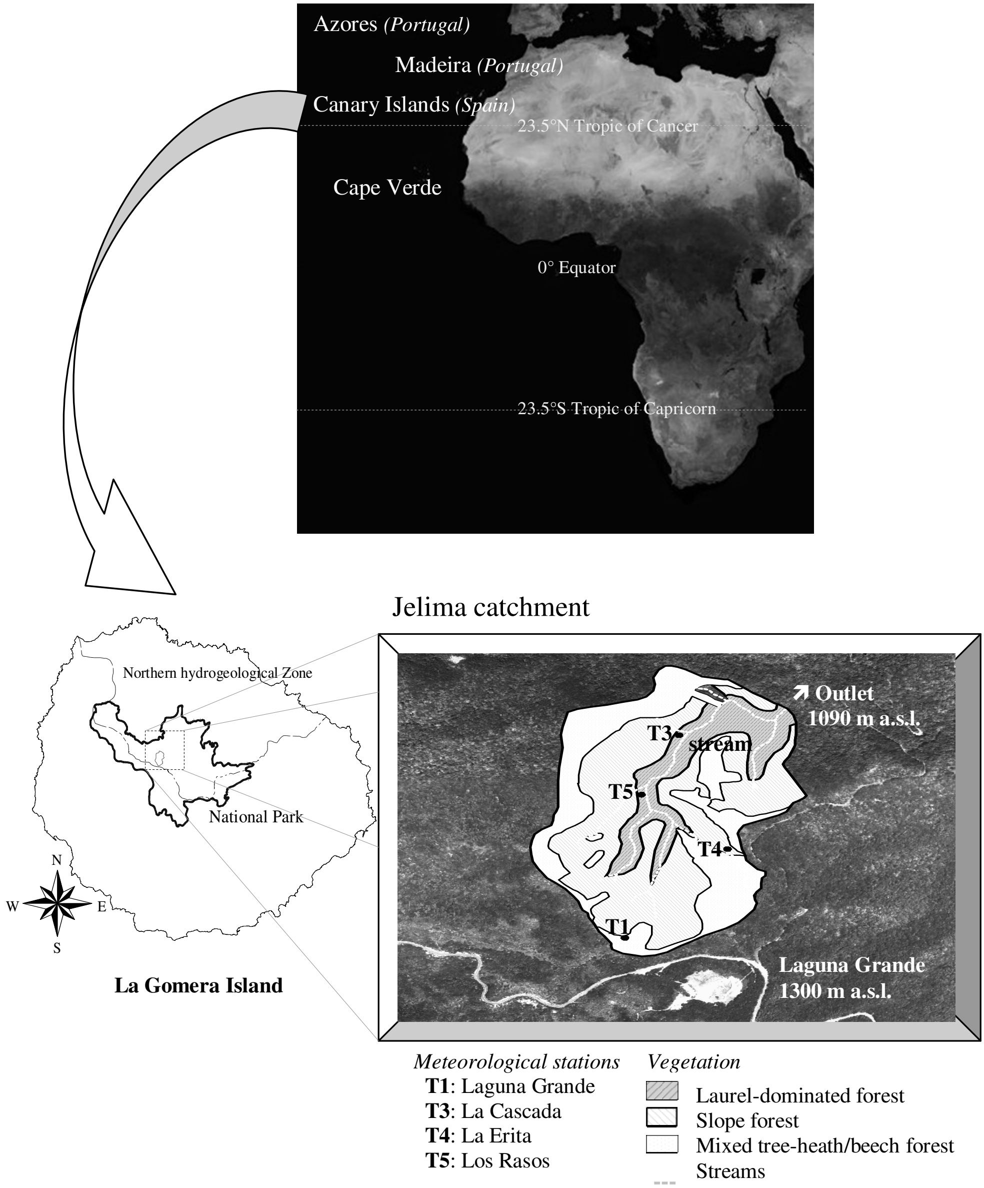


Figure I.1 Above: Location of the Macaronesian region (Cape Verde, Canary Islands, Madeira, Azores). Source after NASA. Below, left: Location of the Jelima catchment within the Northern Hydrogeological Zone of La Gomera (Canary Islands, Spain). Bold line represents the boundaries of the National Park of Garajonay. Right: Location of the meteorological stations and distribution of the vegetation within the study catchment.

The high rainfall and fog incidence of the summit areas (Marzol et al., 1990; Santana, 1990) appears to be a very important source of water. As a first step towards the quantification of aquifer recharge under the prevailing heterogeneous conditions that precluded representative direct measurements of (changes in) groundwater levels, it was decided to quantify each of the components of the water budget (Figure I.2) of a small forested area.

The hydrological cycle in a forested area subject to frequent fog is illustrated in Figure I.2 and described briefly below (Bruijnzeel, 2000). Water inputs consist of rainfall and fog. Part of the rain falls through gaps in the canopy and reaches the forest floor directly (so-called 'direct' or 'free' throughfall) while the remainder strikes the vegetation. Part of this water evaporates directly from the wetted canopy during and shortly after the storm (rainfall interception or wet canopy evaporation) and the rest of the water drips from the leaves (as crown drip) and runs down via the trunks (as stemflow). Crown drip and direct throughfall are usually taken together as 'throughfall' as it is impossible to measure them separately. In the case of fog, which consists of much smaller droplets, the water intercepted by the canopy (effective fog) partly evaporates and partly drips to the ground after saturation of the leaves is reached. Fog interception is not likely to produce stemflow because of the small amounts involved and the presence of mosses and epiphytes on the stems in many cloud forests. The sum of throughfall and stemflow (from rainfall and fog) arriving on the ground is called net precipitation and this water may infiltrate into the soil or be lost from the site via overland flow if the rainfall intensities exceed the absorption capacity of the soil. Depending on the openness of the canopy and the resulting degree of irradiation of the forest floor, some water may be evaporated again. The water which infiltrates into the soil can be taken up by the roots and used in the transpiration of the vegetation. Depending on the vertical distribution of soil hydraulic conductivity and the presence of impeding layers governing hydraulic potential gradients the rest of the soil water either drains slowly downslope as throughflow or vertically to the groundwater table and ultimately becomes streamflow. Both lateral and vertical flow are intensified temporarily during periods of heavy rain (DiCarlo et al., 1999). Rapid lateral near-surface flow may occur during intense rainfall as perched water tables develop temporarily above impeding layers in the soil (Bonell, 2005). Summarizing, groundwater recharge may be estimated fairly accurately by taking the deep seepage ('leakage') as the remaining unknown element in the water balance equation and measuring the other components.

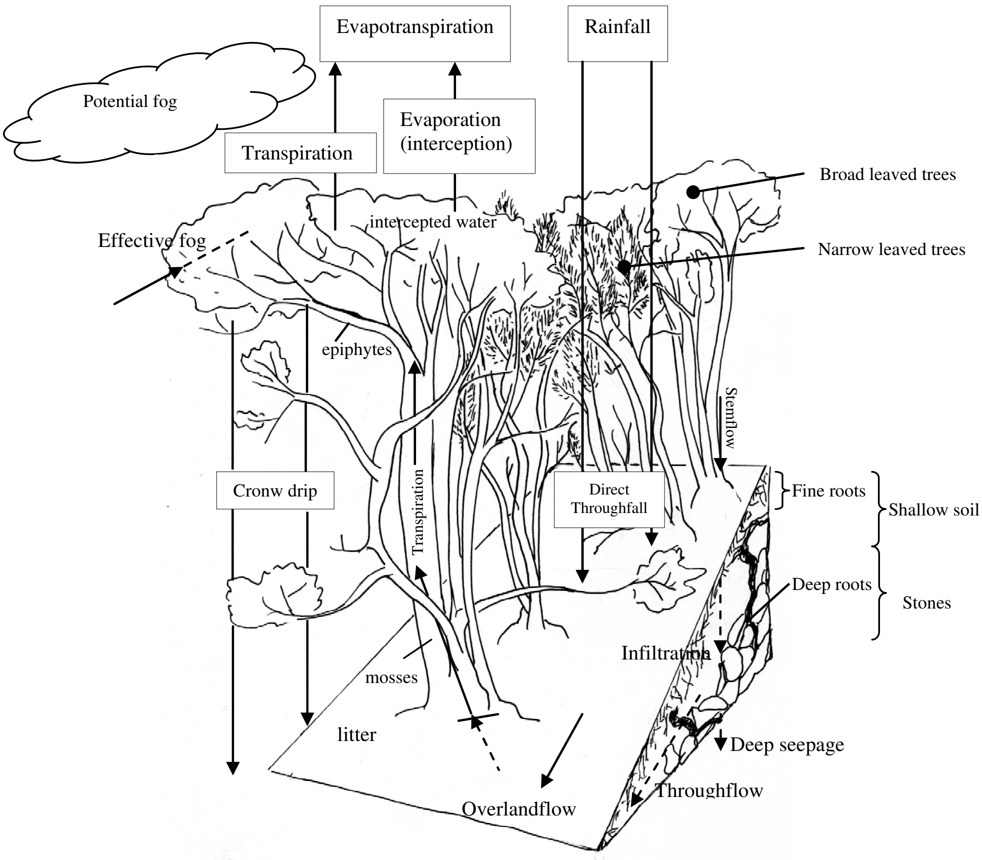


Figure I.2 The hydrological cycle in a ridge top forest subject to frequent fog.

Several studies have measured or estimated individual components of the forest water budget in the Canaries. In the case of rainfall and fog interception, some of the first published studies were those by Ceballos and Ortuño (1942) and Kämmer (1974), followed by Santana (1986), Marzol (1987) (2002) and Aboal (1998). Kämmer (1974) and Höllerman (1981) studied the reasons why the *Laurisilva* on the island of Tenerife is able to survive in a climate which has five dry months. Both authors concluded that the reduction in evapotranspiration in summer due to frequent fog was more important than the actual water contributed by the fog. However, there was a difficulty in quantifying amounts of fog incidence during times of rainfall and strong wind, and therefore no reliable annual totals of fog incidence are available as yet.

It is well known that exposed mountain summits and ridges receive the highest amounts of fog water (Bruijnzeel et al., 2005; Kämmer, 1974; Weaver, 1972). This was also confirmed by the studies conducted by Marzol (2005) in the Anaga Mountains (Tenerife), where as much as 13.6 mm of water were collected in a day period using a standard screen fog collector placed at a particularly exposed site. Conversely, negligible amounts of fog were collected above the canopy of a typical *Laurisilva* site (also in Tenerife) by Aboal (1998). These examples confirm the spatial and temporal complexity of the fog phenomenon at the landscape scale. They also illustrate the importance of the specific location of a site in terms of topography and exposure, elevation and, therefore, microclimatic conditions (wind), but also in terms of the methodology used to evaluate any fog contributions (e.g. type of fog collector, net precipitation measurements, isotope mass balance approaches; Bruijnzeel et al. (2005)).

Measurement of rainfall is not exempt of uncertainties either and the 'true' precipitation that enters the gauge is subject to the size of the gauge orifice, splash-in or out, evaporation, wind effects, location and orientation of the gauge as well as the site itself (topographic and exposure effects) (FØrland and Hanssen-Bauer, 2000; Yang et al., 1998). To date, no wind corrections have been applied to rainfall measurements in exposed headwater areas in the Canaries and previous results must therefore be regarded as underestimates (Holwerda et al., 2006a).

With regard to the evaporative conditions present in the forests of the Canaries, the evergreen *Laurisilva* has developed various adaptive strategies to mitigate effects of high heat loading and excess evaporation as well as to help overcome prolonged periods of low rainfall. These include hard leaves with a protective wax layer as well as an extended root system, thick furrowed bark and a dense canopy that effectively shades the surrounding ground (Aboal, 1998). Thus, water losses due to transpiration and interception by the vegetation can be expected to be more relevant to the water budget than evaporation from the forest floor in laurel-dominated forests. Similar information for the *Fayal-Brezal* is lacking where evaporation rates can be expected to be different due to the more open canopy structure and frequent occurrence of fog.

Several ecophysiological studies in laurel-dominated stands have been carried out in Tenerife that quantified transpiration for some of the more abundant species in these forests, such as *Laurus azorica* and *Myrica faya* (Jiménez et al., 1996; Jiménez et al., 1999; Zohlen et al., 1995). High transpiration rates occurring throughout the year and leaf conductance measurements revealed a weak stomatal control suggesting limited influence on sapflow rates and stomata by meteorological factors or soil water status in these forests (Jiménez et al., 1996; Jiménez et al., 1999). A recent study on transpiration and canopy conductance carried out in native pine forest in northern Tenerife at 1650 m that was under the influence of fog (Luís et al., 2005) revealed stomatal control during highly evaporative conditions. However, to date there is lack of this kind of information for the main species of the fog-affected mixed tree-heath/beech forest found on the upper slopes and exposed ridges of La Gomera.

According to a study by Aboal (1998) in Agua García (Tenerife), the water budget of the *Laurisilva* can be affected considerably by evaporation of water intercepted by the vegetation. It was demonstrated that net precipitation may be reduced by up to 50% in dense valley-bottom forest apparently receiving negligible contributions by fog. Such a reduction in net precipitation, coupled with the high hydraulic conductivity and high water retention capacity of the highly organic volcanic soils could well explain why the intensity of the average rainfall does not produce surface flows in the *Laurisilva* zone other than during rare and temporary events, observed by Höllerman (1981). Nevertheless, some volcanic soils have been shown to become water repellent due to natural factors such as the drying out of organic matter, the presence of resins and waxes, and significant variations in soil water content (Doerr et al., 2000; Jaramillo et al., 2000). It is important to detect water-repellency because it adversely affects the hydraulic and water retention properties of the soil (DiCarlo et al., 1999). This, in turn, may alter preferential flow patterns of water and solutes and cause irregularities in soil water content (Jamison, 1945; Wallis and Horne, 1992). The reduction of soil hydraulic conductivity (van Dam et al., 1996) and infiltration capacity could well increase the possibility of overland flow, and enhance moisture loss due to evaporation (Scott and Van Wyk, 1990). This, in turn, could easily promote soil degradation (Shaskesby et al., 1994) on steep slopes, as in the Garajonay National Park where gradients can be up to 50%. With regard to losses of water due to shallow lateral throughflow or aquifer discharge, no specific studies of runoff generation have been conducted in the forest belt of the Canaries. The majority of springs found in the central sector of the Garajonay National Park are very small (with an average discharge of 0.5 L/s) whereas some springs have intermittent flows (Consejería de Obras Públicas, 2003).

Summarizing, the paucity of previous integrated forest hydrological investigations in the Canaries in general, and in upland La Gomera in particular, combined with the need for sound hydrological information to help plan local water resources, forest and erosion management policies, led to the formulation in 2001 of a process-based forest hydrological thesis.

I.2 OBJECTIVES

The objective of the present study concerns the evaluation of some of the components of the water balance in order to evaluate the net water inputs to the subsoil of a small forested area in complex volcanic mountainous terrain in the *Laurisilva* zone of central La Gomera. This study deals with the surface soil characterization, water fluxes above and below the canopy, and the physiological response of (ridge top) vegetation to changes in weather and soil moisture conditions. As part of this process, empirical models of rainfall interception as well as of transpiration (canopy conductance) are employed.

More specifically, the following themes are addressed:

A. A preliminary study of the physical and chemical properties of the soils of the study catchment, the degree and persistence of hydrophobicity, and the simulation of hydrophobic behaviour based on the humidity of the soils.

B. The characterization of fog occurrence and rainfall inputs in the study catchment, taking into account other climatic variables (notably wind speed and direction), vegetation type (valley bottom *Laurisilva*, hillslope *Laurisilva* and mixed tree-heath/beech forest on upper slopes and ridges), as well as topography (orientation and gradient of slopes, altitude). Characterization of micro-climatic conditions throughout the basin.

C. Measurement of fog and rainwater interception, and modelling of rainwater and fog interception by the vegetation of the ridges (mixed tree-heath and beech) and the valley-bottom laurel forest.

D. The quantification and modelling of transpiration and canopy conductance of ridge top *Fayal-Brezal* vegetation. The identification of possible leaf traits aimed at mitigating the adverse effects of prolonged dry conditions on vegetation development and survival.

E. The site water balance of ridge top forest.

This analysis of the hydrological behaviour of a typical ridge top forest area, in a headwater catchment in the *Laurisilva* zone, is expected to be useful in the management of forested catchments within the Garajonay National Park.

Chapter II

STUDY AREA
AND
GENERAL METHODOLOGY

II STUDY AREA AND GENERAL METHODOLOGY

This chapter provides a general physiographic description of La Gomera Island and the study catchment in order to better understand the hydrological processes taking place in the catchment as described in subsequent chapters.

II.2 PHYSIOGRAPHY OF LA GOMERA

II.2.1 Location and topography

The Canary Archipelago (Spain) is roughly located between 27° 30’ and 29° 30’ N latitude and between 13° 15’ and 18° 15’ W longitude, in the Atlantic Ocean off the coast of Northwest Africa (Figure I.1). It consists of seven main islands (from East to West: Lanzarote, Fuerteventura, Las Palmas de Gran Canaria, Tenerife, La Gomera, La Palma, and El Hierro). Together with the Cabo Verde islands, the Azores and Madeira, the Canaries form the so-called Macaronesian region (i.e. the geographical group of central Atlantic Islands between 10°N and 40°N).

La Gomera Island is located in the middle of the triangle delimited by the following islands: Tenerife, La Palma and El Hierro. It is the second smaller island of the Archipelago with 370 km^2, has a rounded shape with the extension from the eastern to the western side of 25 km being slightly greater than that from the North to the South (22 km) (Figure I.1). The principal divide runs from east to west and breaks up La Gomera Island into a northerly and a southerly slope. Its maximum elevation is 1,484 m above mean sea level at Garajonay peak and its perimeter is 118 km. Despite the presence of a central plateau situated at ca. 1,000 m elevation, the slopes towards the numerous gullies draining this central area can be abrupt, with many slopes exceeding 30º.

There are four main gullies (*barrancos*): La Villa, Valle Gran Rey, Vallehermoso and Hermigua, and four secondary gullies: Santiago, La Rajita, Majona and Las Rosas (Figure II.1). On the northern slope (and indeed on the island as a whole), the biggest (fifth order) drainage basin is called Vallehermoso (34.2 km^2), with wide and long valleys and a pronounced dendritic drainage network forming a very rugged relief (Arozena, 1991). The Jelima subcatchment where the present detailed studies took place is situated in the headwater area of the Vallehermoso basin (Figure II.1).

II.2.2 Geology

La Gomera Island consists of an old shield volcano whose last activity took place in the Miocene era (10 Ma ago) (Carracedo et al., 2002). Unlike Tenerife or La Palma, the lack of new eruptive activity has left the landscape to be shaped by morphoclimatic agents throughout the Quaternary (Arozena, 1991; Bravo and Bravo, 1990). The volcanic outcrops are typically basalts and trachybasalts, and can be classified as pyroclastic deposits (lahars, breccias, ashes) and lavas (dykes). Their differential weathering and hardness have given rise to two well differentiated stratigraphic units, which concur with the hydrogeological units defined for the island. From bottom to top these are described as: basal complex, old basalts (lower and upper unit) and horizontal basalts (Arozena, 1991).

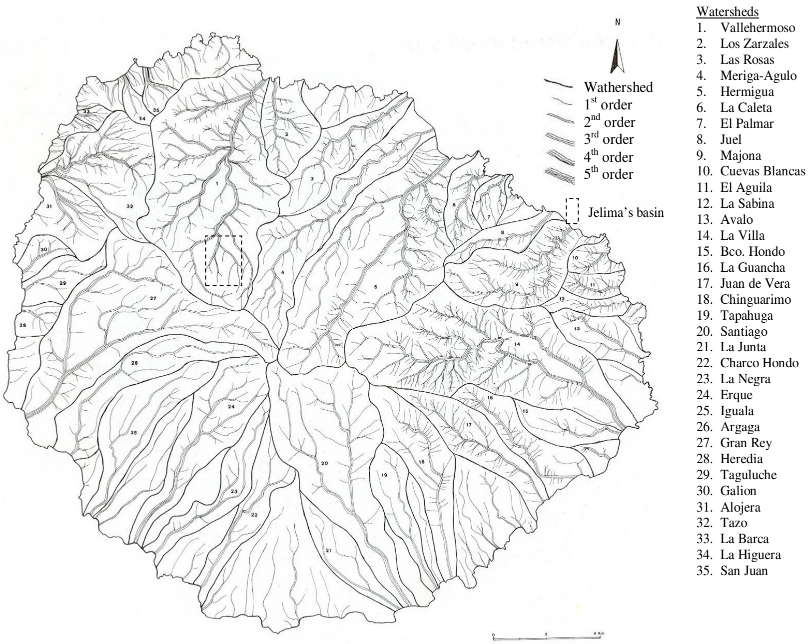


Figure II.1 Main drainage basins and hydrographic patterns on La Gomera. Source: Arozena (1991).

The presence of dense *Laurisilva* forest and intensive chemical weathering has hampered the detailed geological mapping of Garajonay National Park. Briefly, the horizontal basalt series, also called sub-recent basalts, are found extensively in the Park (Figure II.2). These are widespread, thick basaltic and trachybasaltic lava flows alternating with pyroclastic layers. Post-depositional processes have drastically reduced the porosity of the pyroclastic deposits which were originally highly permeable. Hence, these intercalated layers of low permeability disrupt the flow of water percolating through cavities and cracks (Arozena, 1991).

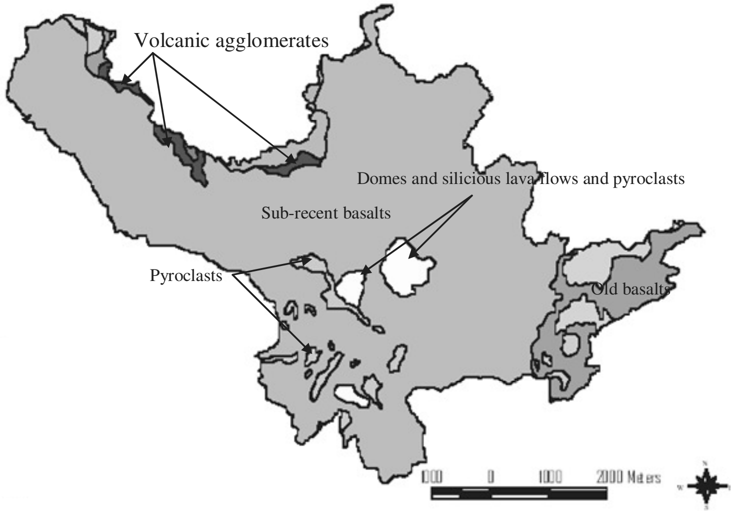
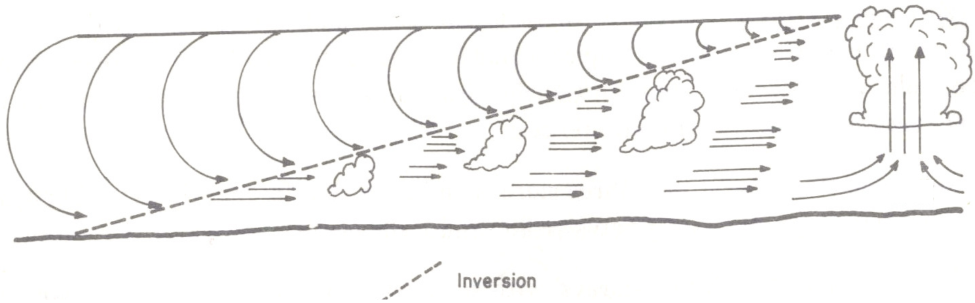


Figure II.2 Geological map of the National Park of Garajonay. Source: more detailed information in Bravo and Bravo (1990).

II.2.3 Climatology

The Canary Islands are located on the south western border of the Azores' anticyclone where warm air coming from the equatorial region is subsiding. At the same time, the islands are subjected to the north easterly trade winds carrying cool and moisture-laden air from the surrounding Atlantic Ocean and forcing the air to rise against the mountains. The ascending air cools until it reaches its condensation point upon which clouds start to form (Barasoain, 1943) (Figure II.3A). This particular climatic setting causes the formation of a thermal inversion within the overall subsidence which in turn leads to the formation of a layer of stratocumulus clouds that is generally referred to as the "sea of clouds" (Dohrenwend, 1972; Font-Tullot, 1951; Marzol, 1990). The thermal inversion impedes the vertical growth of the clouds. The sea of clouds is typically found on the north eastern side of the higher islands (Figure II.3B), with the lifting condensation level (i.e. the cloud base) at about 1,250 m. The LCL depends on the season, in summer the cloud base is about 800 m while during the rest of the time it is >1,000 m (Dorta, 1996). The top of the cloud layer also is subject to seasonal variations in temperatures, and varies between <1,100 m in summer and up to 2,000 m in the rest of the year (Marzol et al., 1996). Also the stratocumulus clouds formation varies during the day depending on the regime of the breeze, relief and oscillations in the thermal inversion. Cloud formation is more frequent at midday on the windward side of the islands whereas land breezes move the clouds out to the sea during the night (Valladares, 1995).

A.



B.

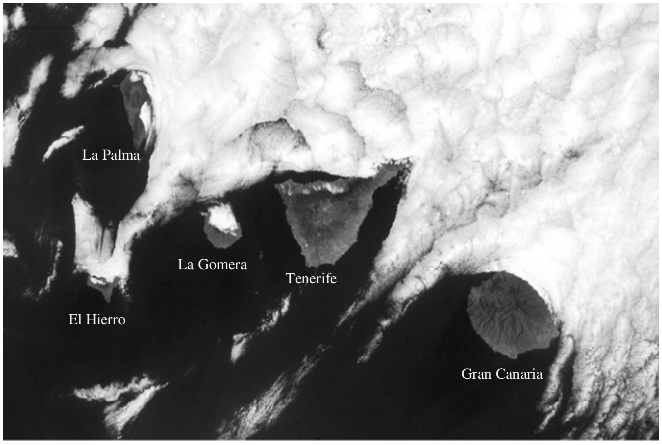


Figure II.3 A. (above) Mechanism forming the trade wind inversion, adapted from Dohrenwend (1972) in Stadtmüller (1986). B. (below) Satellite image of cloud intrusion in the morning of the 30th of June 2001 into the Canary Islands. Source: satellite image from NASA.

As can be expected, the air within the cloud belt is highly humid and cool, although temperatures become milder as one descends towards the coast. Conversely, the layer above the inversion is warm and dry. The stable atmosphere derived from this thermal inversion is one of the most singular climatic characteristics of the Canary Islands (Marzol et al., 1990). However, atmosphere stability can be disturbed by the occurrence of cold and wet currents of air from the North. This situation occurs most frequently during winter when the highest amount and intensities of rainfall are registered. Another disturbance is that by dry and hot Saharan air coming from the Southeast (mainly during summer) (Marzol, 1993).

Thus, these stratocumuli will affect, to a lesser or greater extent, the climate of the northern slopes of the island and the *Laurisilva* woods found on these slopes, depending on the height of the thermal inversion. Therefore, climatological conditions can be very different depending on the altitude of a site, and precise climatological characterization is required. The meteorological network in the National Park consists of 34 stations but the majority are either not functioning properly or have been abandoned (Arévalo et al., 2002). At six stations monthly maximum, minimum and mean temperatures and humidity have been measured by non automatic thermohygrometers since 1986 or 1992. Two stations measured sunshine duration between 1991 and 1995, and at 19 sites, monthly rainfall was measured between 1987 and 1998-1999 (Arévalo et al., 2002).

Based on the above information the general climate on the central plateau of the island, where the National Park and the study catchment are located, was classified as a "Csb-type" climate (Arévalo et al., 2002) in the Köppen classification (type *Csb* implies a Mediterranean climate with a summer and a winter season, where *C* indicates that the coldest month has a temperature between -3 and 18º C; the subscript *s* means that the driest season is summer (evaporation exceeds precipitation); the subscript *b* indicates a warm summer (mean temperature <22ºC)). At this elevation (ca. 800-1,300 m) the weather is characterized by frequent rain events, mostly consisting of light showers and drizzle, whereas fog precipitation occurs when clouds impact against the vegetation (Santana, 1990). Mean annual precipitation is 660 ±247 mm (unpublished data from the National Park; 1987 - 2002), while mean annual relative humidity is >75% may range between 50 and 70% when the sites are situated below the temperature inversion, to 75-100% during times of fog (Marzol, 1990). Solar radiation loads are low due to the frequent occurrence of fog which guarantees mild temperatures during summer with maximum values of 25º C and minimum values of 5-7º C when the stable atmosphere is disturbed by cold oceanic currents during winter and spring. Mean annual potential evapotranspiration (PET) based on 14 years of information on temperatures and estimated by the Thornthwaite equation is 636 mm ± 63 (std) (Arévalo et al., 2002).

II.2.4 Vegetation

The laurel-dominated forest vegetation commonly known by the name of *Laurisilva* includes several subtypes which together represent ca. 23% of the total land surface of the island of La Gomera (Consejería de Obras Públicas, 2003). To date, 53% of the forested area is protected under various environmental policies, and more than 38% corresponds to the National Park of Garajonay located in the centre of the island (3,984 ha) (Consejería de Obras Públicas, 2003). More than half of the Park's area is covered by the type of tall laurel-dominated forest found in the northern valleys and slopes where humid conditions are guaranteed throughout the year, whereas mixed tree-heath/indigenous beech forest (*Fayal-Brezal*) is found on ridges and peaks (Figure II.4). *Fayal-Brezal* represents a kind of degraded laurel forest that is more exposed to the prevailing winds and fog than the more sheltered slope and valley forests dominated by laurels. A stunted form of tree-heath bush (*Erica arborea*) occurs on the most exposed ridges and peaks. Vegetation height decreases when going from sheltered valley bottoms (maximum and average canopy heights of ca. 24 m and ca. 13 m), via intermediate slope positions (maximum and average canopy heights of 18-21 m and 11-13 m), to the ridges (maximum and average canopy heights of 12 m and ca. 6 m) and the most exposed peaks (<1 m) (Golubic, 2001). Distribution of the vegetation within the National Park is shown in Figure II.4 whereas examples of the respective forest types are shown in Figure II.6. A more detailed description of the main vegetation types is given in section II.2.3.

II.2.5 Soils

The volcanic soils of La Gomera are old and have evolved without any rejuvenation since the last eruption in the Miocene era. As such, they have been subjected to leaching, weathering and various geomorphological processes (including surface erosion and mass movement) for extended periods of time. Recently, the soils of the National Park were studied by Rodríguez et al. (2002) who distinguished 21 different soil types based on climatological and age factors, as well as geological, topographical and vegetation factors. The soils can be grouped into eight units as shown in Figure II.5 (Rodríguez et al., 2002), two of which are found in the study catchment: andisols and leptosols (FAO, 1998), which are described in detail later. Generally speaking, the humid conditions prevailing in the Park have favoured the development of an udic type of soil hydrological regime (soils are never dry during >90 consecutive days) and the genesis of umbric, melanic and fulvic horizons. The combination of prolonged leaching and weathering on the one hand, and the steep topography on the other, has resulted in most of the soils being rather infertile, as well as relatively shallow on the steeper slopes.

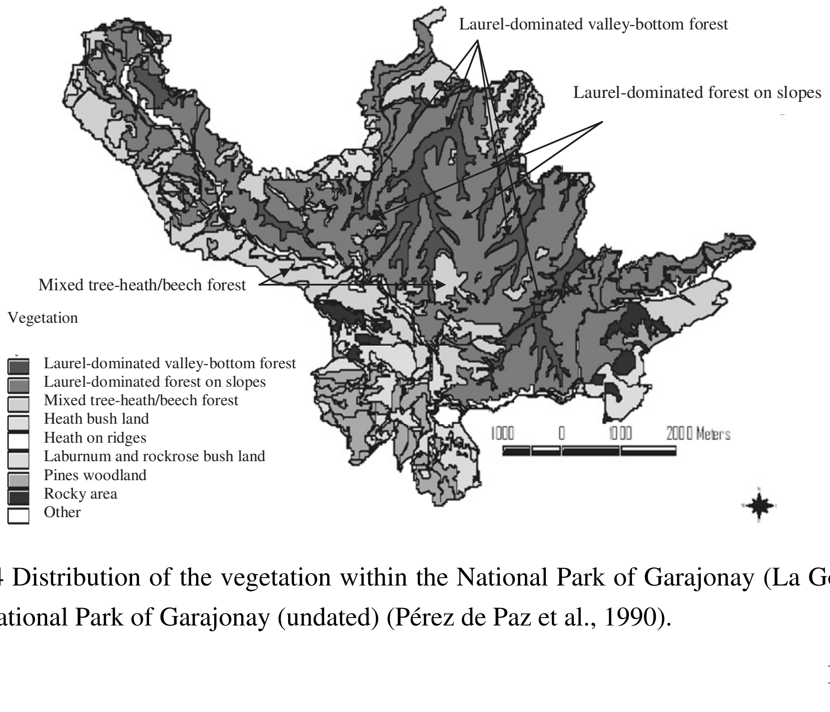


Figure II.4 Distribution of the vegetation within the National Park of Garajonay (La Gomera). Source: National Park of Garajonay (undated) (Pérez de Paz et al., 1990).

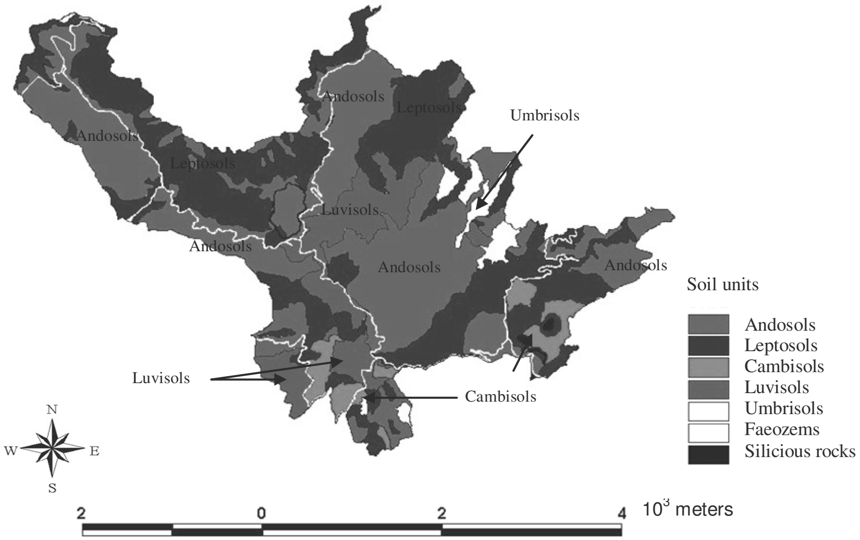


Figure II.5 Soil type distribution within the National Park of Garajonay (La Gomera) (FAO soil classification). Source: modified from Rodríguez et al. (2002).

Laurel-dominated valley-bottom forest *Laurel-dominated on slopes forest* *Mixed tree-heath/beech forest* *Heath forest in the ridge* *Bush-heath (above)*
Laburnum and rockrose bush land

Figure II.6 Vegetation types in the National Park of Garajonay (La Gomera). Top panel: General view over the National Park; letters refer to bottom panels illustrating the respective vegetation types. Source: modified from Rodríguez et al. (2002).

II.3 DETAILED SITE CHARACTERIZATION

II.3.1 Study catchment and experimental plots

To study the water inputs to a headwater catchment area, the spatial and temporal variability of these inputs, rates of soil water uptake by the chief vegetation types identified in the previous section, and groundwater recharge, the 44.0 ha Jelima catchment (‘*Barranco de Jelima*’ in Spanish) was selected. The Jelima catchment is situated in the northern hydrogeological zone of La Gomera, in the headwater area of the Vallehermoso drainage basin (Figure II.7) and within the Restricted Zone of the Park (implying that access is permitted to researchers and Park technicians only). The study catchment is more or less rectangular in shape, has a northeasterly orientation and is located between 1090 and 1300 m a.s.l. at 28^0 17’ 41’’ northern latitude and 31^0 08’ 06’’ western longitude. Owing to its exposure to the trade winds and its elevation, the Jelima basin is influenced by the stratocumulus deck throughout the year.

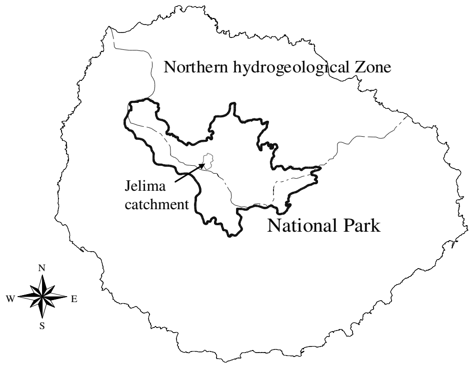


Figure II.7 Location of the Jelima catchment within the National Park of Garajonay, La Gomera.

A general map of the catchment’s relief is shown in Figure II.8. The highest point of the basin is “*el Cabezo de la Laguna*” in the South at 1304 m elevation. On the eastern catchment boundary and descending along the *Juego de Bolas-Laguna Grande* road towards the North, a number of hill crests occur: “*el Cabezo de las Jaras*” (1281 m), “*la Erita de Jelima*” (1222 m) and “*el Chamusco*” (1213 m) after which the road (and catchment boundary) winds down to “*la Pasada de Jelima*” (1090 m) which marks the outlet of the drainage basin. Going back up along the western boundary of the catchment, the basin borders “*el Cabezo Alto*” (1250 m), “*Lorito Plantado*” (1207 m) and “*los Lomos de los Cardos*” (1274-1286 m) (Figure II.8).

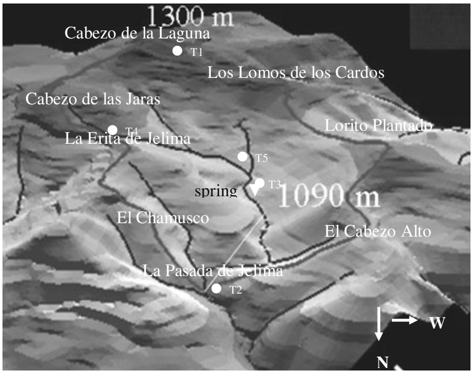


Figure II.8 General topographic map of the Jelima catchment area and chief hilltops. Also shown are the locations of the five experimental plots associated with climate stations T1-T5 (see Section II.3 for details).

Topographically speaking, the upper part of the basin is very steep and the intermediate zone is relatively level, whereas the lowermost part is again extremely steep (Figure II.9). Most slopes are between 10 and 30% but gradients may reach 60% on the upper slopes just below the crests and in the lower parts of the catchment close to the main drainage lines (Figure II.10). Most of the slopes have an easterly orientation, exposing them to the moisture-bringing trade winds (Figure II.10).

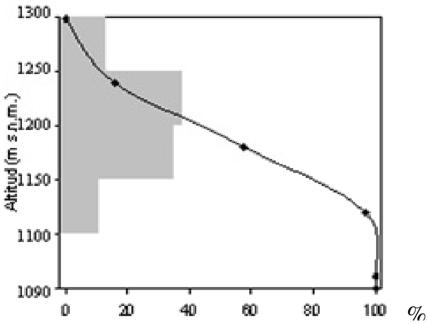
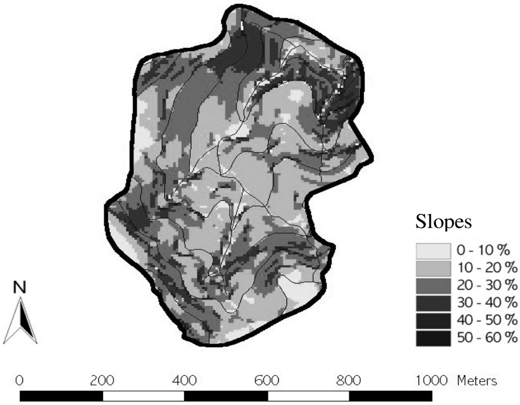


Figure II.9 Hypsometric curve of the Jelima catchment. Shade bars are the shade frequency distribution.



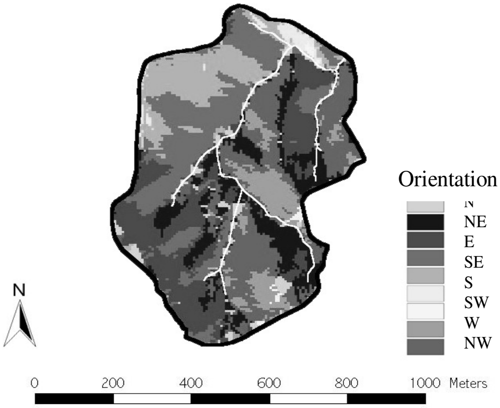


Figure II.10 Slope orientation map (left panel) and slope gradient map (right panel) of the Jelima catchment.

II.3.2 (Hydro)geology

The horizontal basaltic series in the upper parts of the Jelima catchment have been mostly removed by erosion in the past, favouring the extension of the Vallehermoso basin towards the South (Arozena, 1991). In the central zone of the Jelima catchment, layered basaltic series are exposed and an isolated and intermittent spring flows from the cracks in the 5 m high basaltic rock wall above an impermeable layer at approximately 1150 m altitude. The spring discharges into a gully, 350 m long as measured from the springhead to the outlet, with a mean slope of 14%. The lithology varies along the gully: some stretches are basaltic and the water flows without infiltrating, and produces pools, other stretches are permeable and the water disappears, leaving these stretches dry. Due to its morphological and geostructural characteristics, the Jelima basin has a low drainage density (0.8 km^{-1}), also because of the highly permeable soils. The basin is classified as a zero order catchment because the only spring is not perennial, although during exceptionally high rainfall intensities secondary channels will contribute water to the main gully.

II.3.3 Vegetation

The Jelima catchment is covered by so-called '*Monteverde de barlovento*' vegetation which consists of various forms of windward laurel-dominated and heath forest. According to Arozena (1991) this phyto-geographical formation is called in full: '*Laurisilva y Fayal – Brezal de cuencas hidrográficas poco pendientes*' (*Laurisilva* and *Fayal-Brezal* of moderately steep catchment areas) within which three main groups of vegetation are defined: (i) '*Laurisilva de fondo de barranco con viñátigo*' (valley-bottom *Laurisilva*), (ii) '*Laurisilva de* *ladera de umbría'* (shaded hillslope *Laurisilva*), and (iii) '*Fayal-Brezal arborescente de la divisoria principal*' (arborescent *Fayal-Brezal* forest as opposed to the more stunted variety found on exposed summits). In a detailed survey of the area Golubic (2001) distinguished nine different vegetation groups but these can be regrouped in the three main types described just now (Figure II.11).

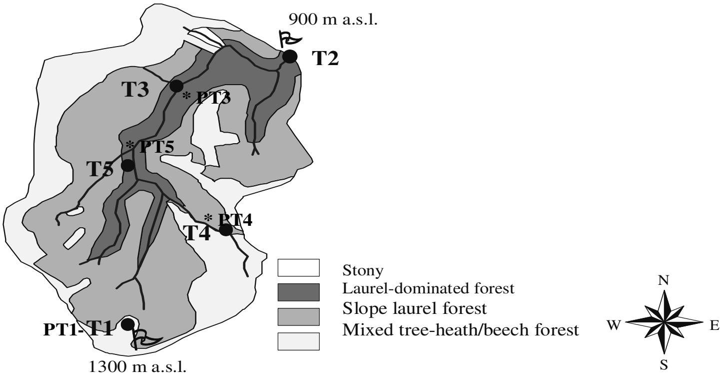


Figure II.11. Distribution of the three main group of forest in the Jelima catchment according to Golubic (2001). Locations of vegetation plots (*, PT1-5) and climatic stations (●, T1-5) added.

Each of the vegetation types is described briefly below and largely follows Golubic (2001) for the valley-bottom and hillslope *Laurisilva* whereas additional observations were made by the author in *Fayal-Brezal* (Table II.1, Table II.2, Table II.3).

Table II.1. Location and basic characteristics of the plots in Figure II.11.

Forest site	Code	Plot Surface m^2	Altitude m a.s.l.	Orientation	Vegetation type[1]	Slope º
La Pasada[2]	-	-	1090	NE	Laurel-dominated forest	35-40
La Cascada[1]	PT3	200	1140	ENE	Laurel-dominated forest	25-35
Los Rasos[1]	PT5	200	1170	NE	Laurel-dominated forest	15
La Erita[1]	PT4	200	1220	SW	Upper slope forest	23
Laguna Grande[2]	PT1	300	1265	NE	Tree heath/beech forest	15-30

[1](Golubic, 2001); [2] (this study)

Laurel-dominated valley bottom forest

The laurel-dominated valley bottom forest in the Jelima catchment belongs to the so-called *Pruno-Lauretalia azoricae* and *Ixantho-Laurion azoricae* associations. Because this type of forest is located in the lower most positions close to the streams, conditions are shadowy and humid (Figure II.6a). The tree canopy is evergreen with a high leaf density (LAI = 6.9 ± 0.8), and has an average height of 12-13 m with a maximum of about 24 m). The understory is poorly developed under these shady conditions and ground cover consists mainly of ferns, of bryophytes on the soil surface, tree trunks and rocks, and to a lesser extent of lichens. This forest type represents about 13% of the total catchment area (Figure II.11). Floristically, the La Pasada site near the catchment outlet was dominated by *Laurus azorica* (Seub.) Franco (*loro* in Spanish) (30%) and *Picconia excelsa* (Ait.) DC. (*palo blanco* in Spanish) (27%), with a sizable contribution by tall and narrow *Persea indica* (L.) K. Spreng. trees (*viñatigo* in Spanish) (17%) (Table II.3). Going up slightly in altitude but remaining close to the main stream, in the La Cascada plot (PT3) *Picconia excelsa* trees were still numerous in the second vegetative layer whereas *Persea indica* disappeared in favour of tall and narrow *Laurus azorica* trees and multiple-stemmed *Ilex canariensis* Poir. (*acebiño* in Spanish; Table II.3). Ferns were largely found close to the streams. Moving up another 30 m in elevation to the Los Rasos plot (PT5, Table II.1) the floristic composition and structure were similar to those of plot PT3 although the appearance of the first *Myrica faya* (Ait.) trees (Table II.3) did increase overall mean canopy height and DBH slightly (Table II.2).

Laurel-dominated forest on slopes

The protection against direct radiation provided by topography and vegetation is reduced as one rises from the valley bottoms to the crests of the slopes and this has consequences for the floristic composition of the forest. In the slope forest represented by the La Erita plot (PT4, 1220 m; Table II.1) *Laurus azorica* became truly dominant with some admixtures of *Myrica faya* and tree heath (*Erica arborea*) (Table II.3). Although *Ilex canariensis* is normally found in slope forests, it was absent in the investigated plot. Slope forest occupied about 60% of the Jelima catchment (Figure II.11). The *Myrica faya* trees were old and tall and a large number had multiple stems (Table II.3). Despite the greater exposure of plot PT4, neither the number of tree species nor mean tree DBH seemed much affected although canopy height was somewhat reduced (Table II.2). Most of the dead trees consisted of *Erica arborea* and *Myrica faya*.

Mixed tree heath/beech forest (Fayal-Brezal forest)

On the ridges of the basin (1225-1300 m) the slope forest is replaced by a vegetation that is best described as the "*Brezal de crestería húmedo (seco en verano)*"of Pérez de Paz et al. (1990) or simply as "*Fayal-Brezal*" (Golubic, 2001). This mixed tree-heath/beech forest on the uppermost slopes and ridges occupied around 25% of the catchment area (Figure II.11). On these more exposed locations *Laurus azorica* becomes less important and is replaced by *Erica arborea* as the main species. *Myrica faya* was found in smaller numbers and was not vigorous whereas the overall number of tree species decreased again (Table II.3). The lower density of the *Erica arborea* canopy resulted in a lower LAI value (4.2 ± 1) whereas in addition the size of the trees was reduced as well (ca. 9 m) compared to forest on the slopes and in the valleys

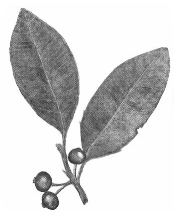
(Table II.3). On the most exposed ridge tops *Erica arborea* forest converted into stunted tree heath bush (Figure II.6e). It is pertinent to mention the abundance of epiphytes, mosses and ferns on the trunks and branches of the trees in the *Fayal-brezal* (Figure II.6d).

Table II.2. Structural characteristics of the four vegetation plots within the Jelima catchment according to Gulobic (2001).

Forest site	Code	Vegetation type[1]	Species per site	DBH, m	Height, m	[1]L.A.I.
La Cascada	PT3	Laurel-dominated forest	36[1]	0.16 ±0.14[1]	11.9 ±6.3[1]	6.9 ±0.8
Los Rasos	PT5	Laurel-dominated forest	42[1]	0.22 ±0.20[1]	12.7 ±5.9[1]	6.9 ±0.8
La Erita	PT4	Upper slope forest	50[1]	0.22 ±0.19[1]	10.6 ±4.4[1]	-
Laguna Grande	PT1	Tree heath/beech forest	38[2]	0.17 ±0.1[2]	8.8 ±2.0[2]	4.2 ±1

[1](Golubic, 2001, DBH> 10 cm), [2] (This study, DBH>7 cm)

Table II.1 Frequency of occurrence of main tree species (%) in the vegetation plots of the Jelima catchment, La Gomera.

Forest site	Code	Type of forest	*Laurus azorica* (*Lauraceae*)	*Erica arborea* (*Ericaceae*)	*Myrica faya* (*Myricaceae*)	*Ilex canariensis* (*Aquifoliaceae*)	*Picconia excelsa* (*Oleaceae*)	*Persea indica* (*Lauraceae*)	Dead trees
									
La Cascada[1]	PT3	Valley forest / *Laurisilva*	44	8	-	24	12	-	12
Los Rasos[1]	PT5	Valley forest / *Laurisilva*	47	6	18	18	6	-	6
La Erita[1]	PT4	Upper slope forest	77	3	10	-	-	-	10
Laguna Grande[2]	PT1	Mixed tree heath	23	60	7	9	-	-	-

[1](Golubic, 2001, DBH>10 cm); [2](This study, DBH>7 cm); Source: pictures after Fernández (1998).

II.3.4 Basic soil physical and chemical characteristics

Two main soil types are found in the Jelima catchment (F.A.O., 1998): Andisols and, to a lesser extent, Leptosols (Figure II.12). Andisols essentially occupy the entire basin except in the uppermost parts and in a small area near the outlet where Leptosols are found (Figure II.12). Generally speaking, Andisols are volcanic ash soils, with deep, dark, organic A horizons. Especially in the case of relatively young Andisols amorphous (non-crystalline) constituents such as allophane, imogolite, and various Al- and Fe-humus complexes are common, inducing strong aggregation (El-Swaify, 1975). Other unique physical properties of (young) volcanic soils are their low bulk density (<0.85 g/cc), high retention of phosphate (> 85%), high oxalate-extractable aluminium and iron amounts (Al_o+Fe_o >2%) as well as difficult clay dispersion, high porosity, permeability, and water holding capacity (Soil Survey Staff, 1998). However, in older and more weathered volcanic soils such as those found in the study area, these typical Andisol characteristics tend to become less pronounced (Bruijnzeel, 1983).

Leptosols on the other hand are very shallow soils with little weathering. Leptosols often develop on steep slopes where there is a constant recycling of material. Their physical and chemical properties resemble those of the parent material, though modified because of the influence of the vegetation (Soil Survey Staff, 1998).

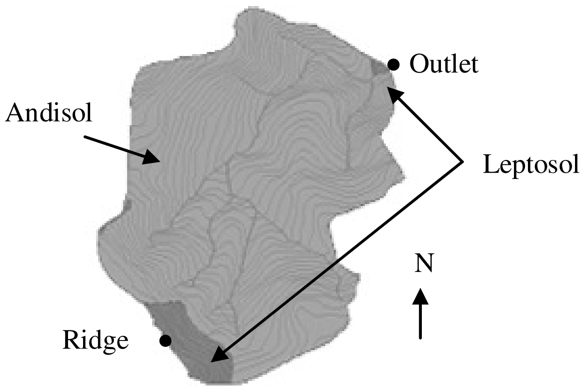


Figure II.12 Soil map of the Jelima catchment (La Gomera) based on (Rodríguez et al., 2002).

The soils in the La Cascada (PT3), Los Rasos (PT5) and La Erita (PT4) vegetation plots were classified as Andisols, whereas the soils of the south western ridges (including the *Fayal-Brezal* plot PT1) and the outlet zone were classified as Leptosols (Rodríguez et al., 2002) (Figure II.12). Most of the Leptosol occurrence coincided with the presence of dykes and outcrops of siliceous rocks.

Almost without exception, the soil texture (*n*=62 samples) was determined as sandy loam (Table II.4) according to the conventional Bouyoucos method. However, this type of volcanic soils tends to aggregate and the Bouyoucos method usually gives a higher sand fraction at the cost of the clay fraction. The problem of determining the texture of highly aggregated soils may be solved in part by applying a Na-resin treatment (Bartoli et al., 1991) although this was not done in the present case.

Andisol profiles in the respective vegetation plots were characterized by well-developed L, F and H horizons (0.05-0.065 m of fresh litter L , 0.02-0.035 m of fermented and fragmented litter F, and 0.005-0.025 m of humus H) (Figure II.13). Organic matter amounted to 33-36% in the surface soils (0-0.05 m) of the valley bottom and slope forests, decreasing to 6-8% in deeper layers (0.25-0.50 m) (Table II.4). Furthermore, these soils are characterized by moderately acid conditions (pH_{H2O} throughout the sampled profile (5.0 ± 0.18), numerous roots in the surface layer (2-10 cm), and deep soil profiles (>1 m). On the other hand, Leptosols (<0.5 m depth) (Figure II.16) had thinner L, F and H horizons (0.045 m of fresh litter, 0.02 m of fermented and fragmented litter and 0.005 m of humus) than the Andisols (Figure II.13), a much higher organic matter content in the surface soil (45%) and much lower organic matter already at shallow depths (1.5% at 0.10-0.25 m) although pH was slightly less acid at 5.2 ± 0.16 compared to that in the Andisols (Table II.4). The higher organic matter content in the Fayal-Brezal is thought to reflect the much wetter conditions on the more exposed ridges which tend to slow down decomposition of litter whereas the slightly higher pH value may be due to the less weathered nature of the Leptisols (Hafkenscheid et al., 2002). Numerous roots were found close to the surface in the top 0.20 m (Figure II.16).

Field capacity of the ridge top soils was determined firstly as the water content of disturbed soils samples under 33 kPa pressure (see Chapter III) and secondly as the water content after 48 h of free drainage from saturated undisturbed soil samples (n=8). Wilting point of the same soils was determined as the water content of disturbed soil samples under 1500 kPa pressure (see Chapter III). Amounts of plant-available water (defined as the moisture content at field capacity minus that at wilting point; (Kessler and Oosterbaan, 1973)) was 0.28 cc/cc in surface soil and 0.32 cc/cc at ca. 30 cm depth. Saturated hydraulic conductivity was measured with the constant-head method (Kessler and Oosterbaan, 1973) on 100 cc core soil samples from the ridge top forest (n=4). The permeability in the surface layer was very high (0.008 cm/s or 6.9 m/day) and still substantial at a depth of 25 cm (0.002 cm/s or 1.73 m/day) (Table II.4).

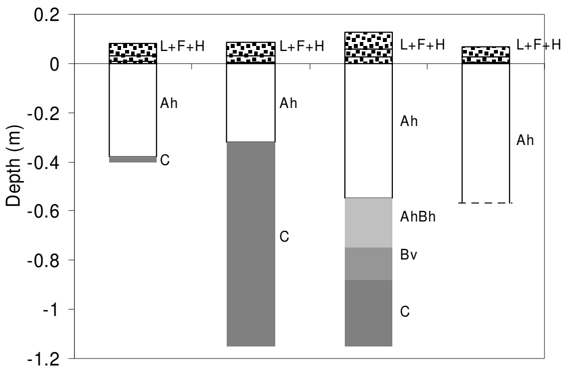


Figure II.13 Soil profiles in the La Pasada (T2), La Cascada (PT3), La Erita (PT4) and Laguna Grande (PT1) vegetation plots. Organic soil layers (L: fresh litter, F: fermented and fragmented litter; H: humus) are indicated above the zero reference depth and mineral soil horizons below it. Source: Golubic, (2001).

Table II.4. Basic physical and chemical properties of the soils at different depths in the main vegetation types of the Jelima catchment.

Soil properties	Texture	pH (H_2O)	O.M. (%)	Field capacity cc/cc	Wilting point cc/cc	K_{sat} (cm/s)
Valley bottom forest	n=14	n=17	n=12			
0.05 m depth	Sandy clay loam	4.84 ±0.5	33.38 ±11.8	-	-	-
0.10 m depth	-	4.72 ±0.3	10.75 ±2.52	-	-	-
0.25 m depth	Sandy loam	5.03 ±0.7	10.6 ±3.45	-	-	-
0.50 m depth	Sandy loam	4.87 ±0.3	5.84 ±3.8	-	-	-
Slope forests	n=36	n=36	n=8			
0.05 m depth	Sandy loam	4.98 ±0.2	36.04 ±6.7	-	-	-
0.10 m depth		-	18.45 ±4.6	-	-	-
0.25 m depth	Sandy loam	4.97 ±0.3	9.38 ±3.25	-	-	-
0.50 m depth	Sandy loam	5.16 ±0.3	8.49 ±7.8	-	-	-
Ridge top forest	n=12	n=12	n=5	n=4	n=15	n=4
0.05 m depth	Sandy loam	5.0 ±0.1	44.7	0.52±0.04	0.24±0.04	0.008 ±0.005
0.10 m depth	-	-	7.44 ±4.35	-	-	-
0.25 m depth	Sandy loam	5.22 ±0.1	1.51	0.54±0.04	0.22	0.002 ±0.0005
0.50 m depth	Sandy loam	5.30 ±0.3	-	-	-	-

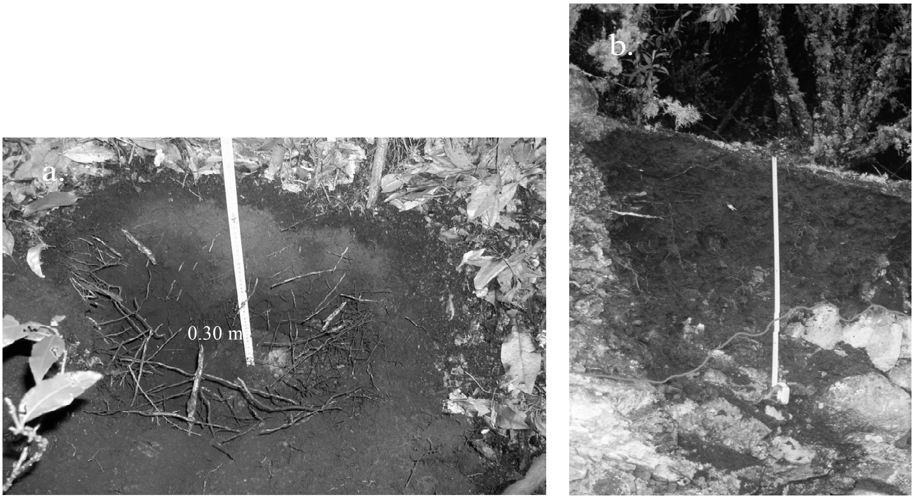


Figure II.14. (a) Soil profile in the ridge top plot. (b) Soil profile on a ridge outside of the plot at 1 km distance. Source of picture (b): Rodríguez et al. (2002).

II.4 GENERAL METHODOLOGY AND INSTRUMENTATION

To examine the spatial variability of rainfall and fog water inputs as well as evaporative conditions experienced by the respective forest types as a function of altitude and exposure five hydrometeorological stations were established in the Jelima catchment that more or less coincided with the five vegetation plots described in section II.2.3 (see Figure II.11 for locations). Table II.5 lists the exact positions of the stations and provides additional basic site descriptions. The first of these stations, called "*La Pasada*" station (T2), was installed in December 2002, and the remaining four stations in January and February 2003. Station T2 was located 20 m above the outlet of the catchment in the bottom of the valley, where the canopy is approximately 20 m high. An 18 m high scaffolding tower was built at this site by National Park staff, with a 2 m mast fixed at the top of the tower extending above the canopy, in which the meteorological equipment was installed. The other three stations – "*La Cascada*" (T3), "*Los Rasos*" (T5) and "*La Erita*" (T4) consisted of 12 m high scaffolding towers (Televes model 360) with a final 2-3 m mast whereas at the ridge top "*La Laguna*" site (T1) the tower was 9 m high (Table II.5). The towers and masts were fixed with nine guy ropes anchored in the soil with a concrete base at 5.5 m from the base of each tower. All stations were equipped with the same meteorological devices installed at 2 m above the canopy (Figure II.16), except at station T5 where the sensors were positioned 1.5-2 m below the top of the canopy.

Table II.5. Basic site characteristics of meteorological stations within the Jelima catchment, La Gomera.

Stations	La Cascada	Los Rasos	La Erita	Laguna Grande
Code	T3	T5	T4	T1
U.T.M. coordinates	X=28°17'42"; Y=31°8'28"	X=28°17'41"; Y=31°8'19"	X=28°17'42"; Y=31°8'14"	X=28°17'41"; Y=31°8'6"
Site altitude (m, a.s.l.)	1140	1170	1220	1270
Orientation	ENE	NE	SW	NE
Height (m)	14	15	15	12
Type of vegetation	Laurel-dominated valley forest		Upper slope forest	Mixed tree-heath/beech forest

All stations measured global radiation (Campbell pyranometer, type SP1110), temperature and relative humidity (Vaisala HMP45C thermohygrometer), wind speed (Vector Instruments, A100R anemometer) and wind direction (Vector Instruments, W200P wind vane). Devices were directly installed on the mast (Figure II.16). Rainfall was measured with a Pronomatic Professional tipping-bucket (0.25 mm per tip) recorder (type Rain-o-Matic; orifice surface 200 cm^2). Fog water was collected with a quarter-sized variant of the Standard Fog Collector of Schemenauer and Cereceda (1994) as modified by Marzol (2002). The 0.5x0.5 m fog collector was built locally using Raschel polypropylene wire mesh with a 65% shade coefficient. It was installed vertically and oriented to the northeast (see also Figure II.16). Further details on rainfall and fog water collection procedures and corrections can be found in Chapter IV. At four of the five vegetation plots/climatic stations (T1, T3, T4 and T5), throughfall and soil water content were recorded (Figure II.16). Throughfall was measured by means of two large recording gauges per plot, each having a collection surface of 0.2 m^2. Therefore, the throughfall collecting area was equivalent to the surface area of 40 standard gauges of 0.01 m^2 each (see also Chapter IV). Soil moisture was measured with two TRIME-IT/EZ time domain reflectometry (TDR) probes per plot that were installed horizontally at 0.15 and 0.30 m depth (no replications per plot). Additionally, eight pairs of sapflow sensors (heat dissipation type; Granier, (1985) were installed in March 2003 in four *Erica arborea* and three *Myrica faya* trees (one pair added as second to one of the sample trees) in the ridge top cloud forest (T1) to measure transpiration dynamics. Further details are given in Chapters VI and VII.

At the La Pasada station (T2, Module 2), the climatic variables were measured every 3 minutes and stored every 15 minutes in a Campbell CR10-X datalogger. Data were downloaded manually every 10 days by National Park staff, cause of the poor coverage. Rainfall, fog, throughfall and soil water data for this station were incomplete with many gaps. At the other stations, all variables were measured every 3 minutes and stored every 15 minutes in a UP Combilog datalogger. Data downloading was carried out automatically via GSM modem (Figure II.15). This technology allowed direct cellular communication and data transmission between the field stations in La Gomera and the work place in Tenerife as long as good network coverage was ensured. Coverage was not ensured by the provider (Telefónica) for the Los Rasos station (T5) (communication Module 5). Therefore, Module 5 (RS485 port) was connected to Module 3 of the La Cascada station (T3, RS232 port) through a port converter. The sapflow data storage system was the same as that used in the other four stations. The associated Module 0 had an independent Combilog datalogger that was connected to Module 1 of the Laguna Grande station (T1) through another port converter (Figure II.15). Thus, sap flow data were obtained at the same time as the climatic and other data collected at the Laguna Grande station. Data were received at 15 minute intervals by the Base Module in Tenerife. In order to save energy the modem connection was opened during1 hour/day only. Power to the equipment of the La Pasada station (T2) was supplied by a 12V-24Ah battery recharged by a solar panel (50W). The remaining stations received their power from 12V - 100Ah batteries recharged in turn by one solar panel (75 W, 1.2 m x 0.5 m) per station. Solar panels were installed on the towers with a southerly orientation and a 40º slope to maximize the number of hours with light (Figure II.16).

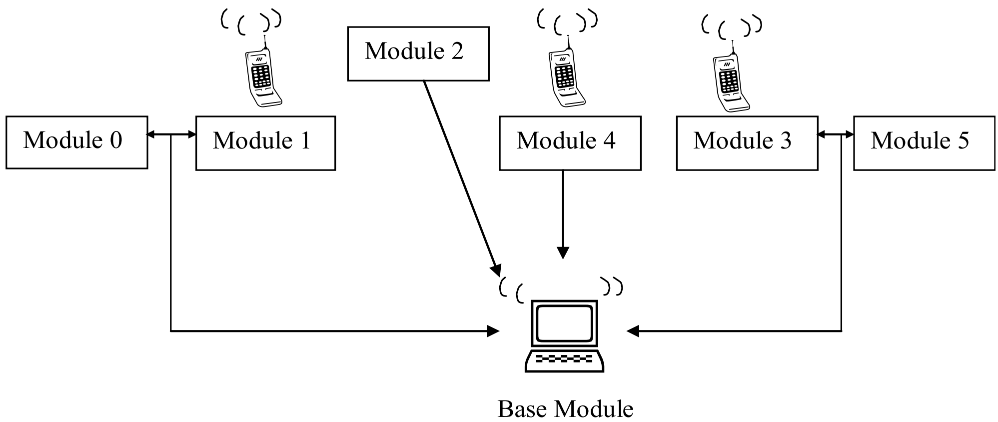


Figure II.15 Communication system between the various stations located in the Jelima catchment on La Gomera and the Base Module in Tenerife used to download the data remotely.

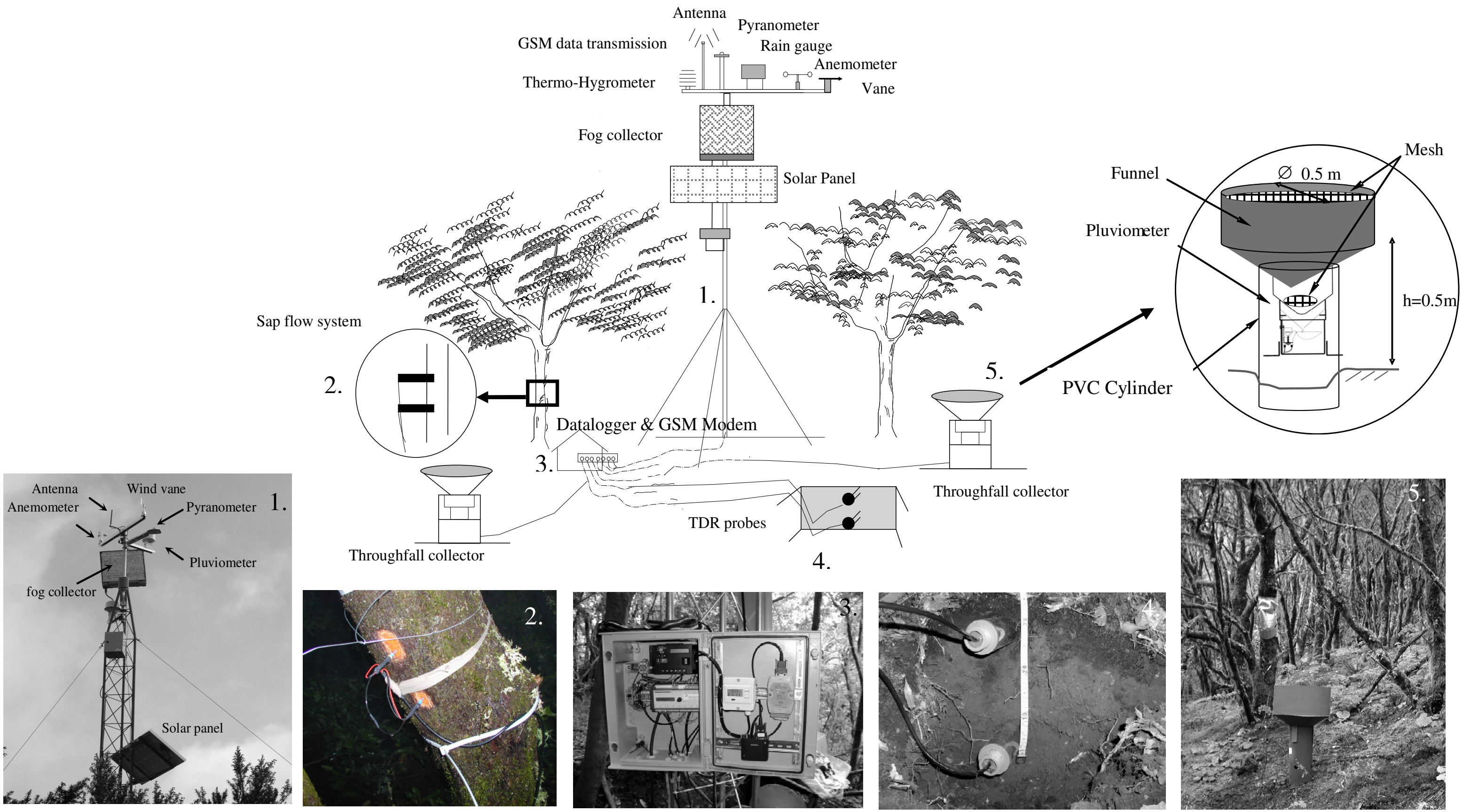


Figure II.16. General hydrometeorological and forest hydrological measurement set-up. (1) Climate station, (2) Sapflow sensors, (3) Data recording, storage and transmission equipment, (4) TDR soil water sensor, (5) Throughfall collector.

Chapter III

SOIL WATER REPELLENCY IN A SUBTROPICAL CLOUD FOREST: A PRELIMINARY ANALYSIS

III SOIL WATER REPELLENCY IN A SUBTROPICAL CLOUD FOREST: A PRELIMINARY ANALYSIS

ABSTRACT

Soil water repellency (hydrophobicity) affects soil hydrological functioning adversely by diminishing infiltration capacity, while increasing surface runoff. This study examines the degree and persistency of hydrophobicity of samples of highly organic volcanic soils from a forested catchment in the Garajonay National Park, La Gomera, Canary Islands. Both the water droplet penetration time (WDPT) and the molarity of ethanol droplet (MED) tests were applied for different gravimetric soil water fractions (w). Time to infiltration (t_i) and contact angle ($\alpha_{l\text{-}s}$) between applied drops and the soil material varied as a function of soil water content. Non-monotonic hydrophobic behaviour was observed, in which hydrophobicity initially increased to a maximum and then decreased as w diminished. Two empirical regressions were fitted to the t_i-w and $\alpha_{l\text{-}s}$-w data sets. It was feasible to quantify the observed hydrophobic behaviour by means of the fitted shape parameters of the regressions. Moisture measurements indicated that soils were repellent within the range of water content available to plants. Possible correlations between water repellency shape parameters and organic matter content were investigated.

Chapter III is a reworked version of the paper "Caracterización de la zona no saturada de un bosque maduro de laurisilva en el Parque Nacional de Garajonay: Hidrofobicidad e implicaciones hidrológicas" (in Spanish) by Regalado, C.M., García-Santos, G., Hernández Moreno, J.M., Pérez Buenafuente, A., and Socorro A.R., (2003). In "*Estudios de la Zona no saturada del Suelo*" (J. Álvarez-Benedi, P. Marinero, ed.), I.T.A. Monograph, Vol. 6, pp. 193-199. ITA, Valladolid (Spain).

III.1 INTRODUCTION

Hydrophobicity or soil water repellency is a phenomenon characterized by the loss of soil wettability and the temporal or permanent resistance of the soil to be wetted again (Doerr and Thomas, 2000). Factors that may induce water repellency include soil drying (including fire) (Díaz- Ferros, 1977), or coating of the soil particles by organic compounds emanating from vegetative decomposition (DeBano, 2000; Moral et al., 2002) or the by-products of metabolic activity of soil microorganisms (Bond, 1969; Chang et al., 2002).

Variations in soil moisture may induce hydrophobicity in some soils, depending on the specific soil characteristics (e.g. sand content), antecedent moisture status, and climatic conditions (De Jonge et al., 1999; Dekker, 1998; Dekker et al., 2000; Wallis and Horne, 1992). Thus, certain soils can be converted to a water-repellent state during a rainless period and become non-repellent again after a series of showers has rewetted them (Dekker and Ritsema, 1994). On the other hand, hydrophobicity can also occur under wet conditions, e.g. because higher amount of organic matter is likely to occur under very humid climate than dry (Jaramillo et al., 2000).

The importance of detecting which soil horizons are potentially susceptible to water repellency lies in the fact that the hydraulic properties may be affected. The soil water characteristic may be modified (Bauters et al., 2000; DiCarlo et al., 1999) and consequently preferential paths for water and solute movement into and through the soil may be altered, causing irregular soil wetting (Wallis and Horne, 1992). Saturated and unsaturated hydraulic conductivities can be modified as well (van Dam et al., 1996), causing a decrease in soil infiltration capacity and increases in overland flow (Scott and Van Wyk, 1990) and surface erosion (Shakesby et al., 1994).

The present study was conducted in the headwaters of the densely forested Garajonay National Park on the island of La Gomera, Canary Islands. The area experiences a seasonal rainfall regime and is underlain by volcanic soils and therefore may be subject to soil water repellency. The specific objectives of this study are: i) to study the possible relationship between soil organic matter content and soil water repellency; ii) to determine soil hydrophobic evolution upon air-drying of the material and to establish critical soil water content levels below which hydrophobic behaviour occurs; and iii) to assess the erosion hazard in the study area associated with soil water repellency.

III.2 MATERIALS AND METHODS

III.2.1 Study area

The present study was carried out in the 44 ha Jelima catchment located in the centre of the National Park of Garajonay on La Gomera between 1,090 and 1,300 m altitude. The topography is mountainous. The steepest slopes are found close to the central gully draining the catchment and just below the ridges. The soils are volcanic in origin and have various andic characteristics (Rodríguez et al., 2002). The catchment is entirely covered with montane laurel forest in which three main types can be distinguished (Golubic, 2001; Pérez de Paz et al., 1990): mixed tree-heath/beech forest on the ridges, laurel-dominated forest on the slopes, and laurel-dominated forest in the valley bottoms. Climatic conditions are characterized by high mean annual relative humidity (>75%) but may vary between 50 to 100% (Marzol, 1990), relatively mild temperatures (average 13.0 ºC, monthly range 8.9 – 19.7 ºC), and a moderate mean annual precipitation total of around 660 mm (National Park, undated). For further physiographic details on the study area the reader is referred to Chapter II.

III.2.2 Sampling design

Three types of soil sampling were carried out within the catchment: firstly, a set of 63 soil samples was obtained for the characterization of soil texture; secondly, a set of 33 soil samples was obtained for the characterization of basic physical (bulk density and porosity) and chemical properties (some andic diagnostic parameters and water repellency). In both surveys samples were taken at four different depths (0-0.03 m, 0.03-0.23 m, 0.23-0.43 m, and 0.43-0.63 m) at randomly selected positions within the three types of vegetation. The third soil sampling was systematic. A rectangular grid (100 x 75 m) covering the entire catchment was used for this (Figure III.1), which resulted in another 140 soil samples collected from the first 0.03 m of mineral soil only after removing fresh, fermented and fragmented litter, and any surface humus for the characterization of water repellency, the plant available water-holding capacity of the soils and the content of organic matter.

Soil texture was determined by the Bouyoucos densimeter method (Gee and Bauder, 1986). Bulk density and porosity were estimated according to Klute (1986). Several andic diagnostic parameters were also determined for a subset of 25 samples. The samples were air-dried and passed through a 2 mm sieve. The pH in NaF (Blakemore et al., 1981), in H_2O, and in KCl as well as soil organic matter content were determined by standard methods (M.A.P.A., 1994). Soil lipids content was obtained by dichlorometane/methanol (9:1 v/v) extraction whereas Al in KCl and oxalate- and pyrophosphate-extractable concentrations of Al (Al_o, Al_p) were determined following Blakemore et al. (1981). The ratio Al_p/Al_o is normally used to distinguish between allophanic ($Al_p/Al_o<0.4$) and non-allophanic Andisols ($Al_p/Al_o>0.4$) (Shoji et al., 1996).

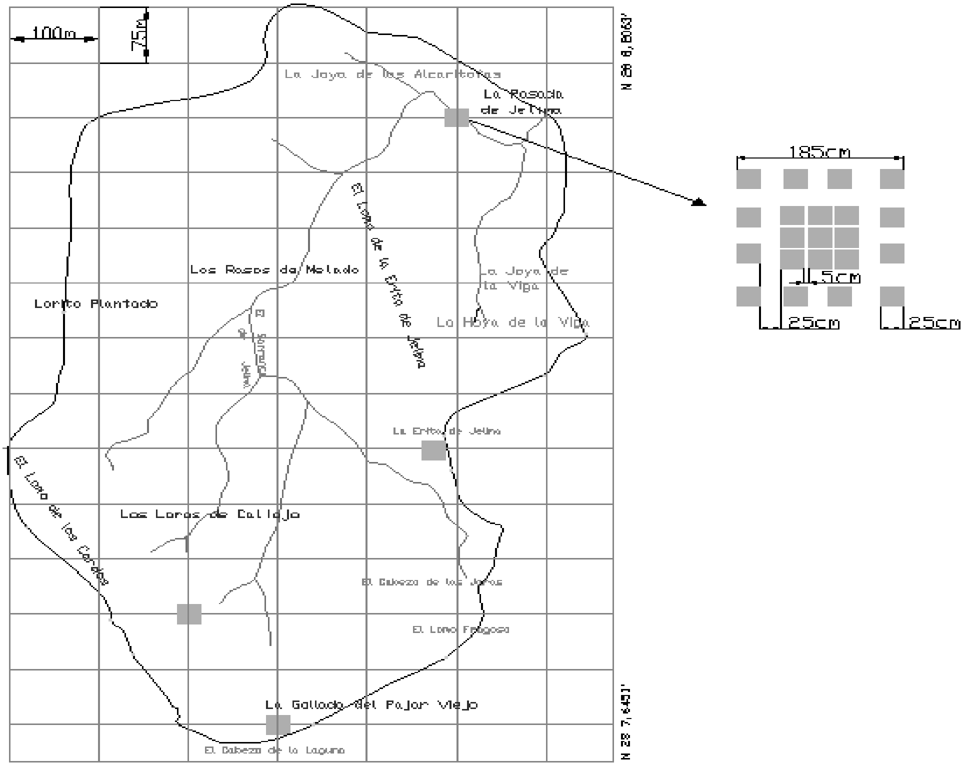


Figure III.1 Systematic soil sampling grid (100 m x 75 m) and locations of four intensive sampling sites (■) within the Jelima catchment.

III.2.3 Water droplet penetration time test (WDPT)

The water droplet penetration time method (WDPT) of Letey (1969) estimates the persistency of soil hydrophobicity by measuring the time to infiltration of a water droplet (t_i) (cf. Annex for details). Persistency is then classified according to an arbitrary but commonly used numerical scale (Table III.1). Recommended conditions in the laboratory are a temperature of 20ºC and a relative humidity of 45% (King, 1981; Letey, 1969), and the droplet size should be larger than the greatest soil pore diameter (Johnson and Dettre, 1993). Therefore, it is advisable to work with a droplet diameter of 4-5 mm or a droplet volume of 0.25 - 0.50 ml (King, 1981; Letey, 1969).

Table III.1 Soil repellency persistence classification as a function of droplet infiltration time according to Letey (1969).

Infiltration time, t_i (s)	Persistency
5	Non-repellent
5-60	Slightly repellent
60-600	Strongly repellent
600-3600	Severely repellent
>3600	Extremely repellent

III.2.4 Molarity of ethanol droplet test (MED)

The molarity of ethanol droplet test (MED) (Letey et al., 2000; Roy and McGill, 2002; see Annex for details) estimates the degree of soil water repellency by means of the molarity of a mixed water-ethanol dilution applied to the soil sample in the form of droplets. The procedure consists of applying a droplet of known ethanol concentration (expressed as the volume percentage of pure ethanol, 95% concentration, present in the mixture; i.e. 1, 2, 3, 4, 5, 6, 8, 10, 12.5, 15, 17.5%, etc.) or of known water-ethanol dissolution molarity (Letey et al., 2000) to the soil sample under consideration, and observing whether the droplet is absorbed within the first 10 seconds. If the droplet remains on the soil surface, a higher ethanol concentration is applied following the same procedure to induce a lower liquid surface tension value (γ_l). This method allows the calculation of the contact angle between the solid and the liquid phase (α_{l-s}) using the following equation (Carrillo et al., 1997; Roy and McGill, 2002):

$$\cos \alpha_{l-s} = (\gamma_l / \gamma_a)^{0.5} - 1 \qquad \text{III.1}$$

where γ_a is the surface tension of water (71.2739 mN/m or dyne/cm) (Roy and McGill, 2002) and γ_l is the surface tension of the water-ethanol mixture expressed in mN/m, which can be derived using the following equation:

$$\gamma_l = 61.05 - 14.75 Ln(\mathrm{M} + 0.5) \qquad \text{III.2}$$

where M is the molarity of ethanol in the mixture (mol/l).

According to Eq.III.1, a higher liquid surface tension value causes a greater contact angle, which induces a slower droplet infiltration. Contact angles between applied droplets and the soil surface typically range between 90-109º (Carrillo et al., 1997; Roy and McGill, 2002). Therefore, wettable soils (i.e. $\gamma_l \approx \gamma_a$) will result in cos $\alpha_{l-s} \approx 1$ (Eq. III.1) and therefore $\alpha_{l-s} \approx$ 90º, and water-repellent soils in α_{l-s} >90º. Recommended ambient conditions in the laboratory are the same as those for the WDPT test (Letey et al., 2000).

III.2.5 Test application procedures

Soil samples were put immediately into plastic bags after removal of leaves and coarse materials (stones, roots). Normally, tests to assess water repellency are conducted on air-dried soils. However, because irreversible changes tend to occur in the structure of andic soils upon drying which would affect soil chemical and hydraulic properties (Jaramillo, 1999; Maeda and Soma, 1992), the samples were initially passed through a 2 mm sieve at the laboratory in their field-moist state. Next, 0.308 m^3 of moist soil material was placed upon transparent plastic Petri dishes (0.14 m diameter and 0.02 m deep; Figure III.2, left). To examine the effect of soil moisture content on hydrophobicity, the moist samples were wetted further with distilled water using a manual spray gun, until they were saturated. The Petri dishes were then closed to avoid water losses by evaporation, and the samples were left for 48 h to allow stabilization and homogenisation of soil water distribution. All samples were weighed and any surface crusts present were broken before starting the test applications.

The WDPT consisted of depositing three water droplets onto the surface of the samples and measuring the time required for the infiltration of the three droplets. Hypodermic needles and syringes with a rubber piston were used to allow better control and precision in producing and positioning identical droplets with a diameter of 4 mm on the soil surface (Figure III.2, right). The average time required for the three droplets to infiltrate was considered to be the infiltration time. In the case of the MED test, three droplets with known ethanol concentration were deposited. When droplets were no longer able to infiltrate (>10 s), the associated molarity was taken.

Both tests were applied on gradually drier samples and measurements were made after each 3 g of weight loss during air drying. Ambient conditions during the test application were 20 ±5ºC and 65 ±5% relative humidity. After the soils were completely air dried (i.e. until constant weight was reached), they were oven-dried at 55, 60 and 105ºC to assess the effect of temperature on hydrophobicity. Some studies have shown that water repellency (WDPT) increases by heating soil to temperatures between 40 and 70 ºC (Crockford and Richardson, 2000; Dekker et al., 1998). The two tests were applied again after each oven-drying. Finally, gravimetric moisture contents (g water/g soil) during the tests were derived based on soil weights during the respective phases (Klute, 1986).

Figure III.2 Left: Soil samples placed in the Petri dishes. Right: Water droplets placed on the surface of the soil sample using a syringe with rubber piston.

III.2.6 Soil water retention

The plant available water-holding capacity of the soils in the Jelima catchment was estimated by determining two points on the water retention curve using the ceramic plate technique detailed in Klute (1986). Measurements of soil water content were made at suctions of 33 and 1500 kPa, which were considered to represent the field capacity (w_{fc}) and permanent wilting point (w_{wp}) of the soils, respectively (Klute, 1986). Field-moist disturbed soil samples obtained during the third sampling (n = 140) were passed through a 2 mm sieve. Next, the samples were placed in rings of 10 mm height and 50 mm diameter and saturated with a 0.005 M $CaSO_4$ solution and tymol for 48 h in order to minimize effects of clay dispersion and organic matter degradation (Klute, 1986). Preliminary observations had shown that a decrease in soil water content significantly affected the volume of the samples. Because this might result in a suboptimal contact between the soil samples and the ceramic plate, and therefore in an overestimation of soil water retention, weights of 700 g were laid on the top of the samples to ensure good contact with the ceramic plate throughout the process (Klute, 1986).

III.3 RESULTS AND DISCUSSION

III.3.1 Soil physical and chemical properties

Soil texture (based on USDA classification) was mostly sandy loam (n = 62) (see Chapter II), regardless of soil depth. However, the proportion of the clay fraction was almost certainly underestimated by the Bouyoucos method because of the highly aggregated nature of the volcanic material (Wada, 1985). As such, a classification as clay sandy loam would probably be more appropriate. The use of alternative methods to achieve optimum peptisation of the material (e.g. using resins, Bartoli et al., (1991)) would be required for a proper estimation of the clay fraction. Soil organic matter and lipid concentrations were clearly stratified, with the highest values found in surface soils (OM = 41.9 ± 12.5%; lipids = 21.2 ± 16.2 mg/g) decreasing with depth (Table III.2). Bulk densities were very low in surface samples (0.6 ± 0.1g/cm^3), because of the relatively high soil organic matter and the volcanic nature of the soils (Wada, 1985) and slightly higher at depth (0.7 ± 0.1g/cm^3). Soils were moderately acid throughout the profile (pH_{H2O}= 5.5 ±0.4) by general cloud forest standards (Bruijnzeel and Proctor, 1995). pH_{KCl} (4.5 ±0.2) was lower than $pH_{H2O,}$ indicating a net positive charge deficit which is characteristic of Al-humus complex (Wada, 1985), and slightly decreased with depth whereas pH_{NaF} (10.6 ±0.9) was higher and slightly increased with depth. Available water-holding capacity of the surface soils was very high at 69 ±30.7% (based on gravimetric moisture contents) and 42 ±18.4% on a volumetric basis (obtained after multiplication times bulk density). This most probably reflects the high organic matter content of the soils.

Table III.2 Averaged (*n* = 33) basic soil chemical and hydrophobic (WDPT and MED test) properties as a function of soil depth.

Depth (cm)	O.M. (%)	Lipids (mg /g)	pH_{NaF}	Infiltration time (s) (WDPT)	Contact angle (α_{l-s}, º) (MED)
0 - 3	41.9±12.5	21.2±16.2	9.2±1.2	944±1197	96.9±5.2
3 - 23	12.0±0.5	2.3	10.9±0.5	86±219	90.9±1.8
23 - 43	10.1±0.5	-	11.1±0.5	0	90
43 - 63	6.9±0.6	0.6	11.1±0.6	0	90

Results obtained with the WDPT and MED repellency tests for different soil depths (n =33) in air dried soil samples showed that although hydrophobic conditions were found in the first 0.23 m of soil (Table III.2), the uppermost horizon between 0 and 0.03 m was significantly more water repellent potentially, most probably because of its much higher organic matter content. Soils layers below 0.23 m depth were perfectly wettable (Table III.2). A somewhat thinner potentially repellent surface layer between 0.04 and 0.13 m depth was found for Andisoils in Colombia by Jaramillo et al. (2000), a finding which was attributed to the high organic matter favoured by a very humid climate. The WDPT and MED test results for soil samples from the first two horizons down to 0.23 m depth (n= 33+140 =173) showed that wettable soils had less than 8% organic matter. However, neither the concentration of lipids nor organic matter content in samples containing more than 8% organic matter correlated very well with the persistency or degree of hydrophobicity as derived with the WDPT and MED tests, respectively. This could be due to differences in the degree of organic matter decomposition and humification (Jaramillo, 1999) but these aspects were not studied in this work.

The spatial distribution of organic matter concentrations in 60 topsoil samples (0-0.03 m) was studied as a function of forest type but no clear correlations were found. About 98% of the samples had high (>30% O.M.) or medium (20%< O.M. ≤30%) concentrations regardless of forest type. However, only 5% of the samples with medium concentrations represented ridge top forest.

III.3.2 Andic diagnostic parameters and soil water repellency: a preliminary analysis

Several andic diagnostic parameters were determined for the 33 samples obtained during the second soil sampling. The relationships between these andic properties and the results of the WDPT tests were studied by means of principal component analysis (PCA). Figure III.3 summarizes the results of the analysis, in which KCl-extractable Al (Al_{KCl}), the ratio between pyrophosphate- and oxalate-extractable Al (Al_p/Al_o), as well as the pH_{NaF}, the pH_{KCl} and pH_{H2O} and O.M. were used as the main variables. Component 1 explained 76% of the observed variability in persistence of repellency. High values of pH_{NaF} (≈11) indicating the presence of allophanic materials (Wada, 1985) were positively related to non-hydrophobicity (fourth quadrant in Figure III.2) whereas high values of O.M. and Al_p/Al_o, which reflect the degree of organo-mineral complexation (Wada, 1985), were positively related to hydrophobicity (see second quadrant). In conclusion, the more weathered, non-allophanic soils with high organic matter concentrations are more susceptible to water repellency whereas allophanic soils (high pH_{NaF} and $Al_p/Al_o<0.4$) do not have such tendencies. The latter conditions were mostly found in deeper layers.

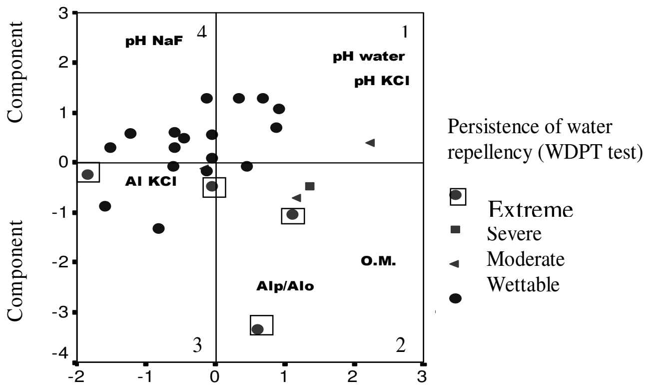


Figure III.3 Relationship between selected Andic diagnostic parameters and hydrophobicity (WDPT test). Wettable soils are shown as points and the rest of the symbols represent different grades of hydrophobicity.

III.3.3 WDPT and MED tests: effects of air-drying

Water droplet infiltration times (t_i, WDPT) and contact angles (α_{l-s}, MED) were determined across the entire soil water spectrum, i.e. from saturated conditions until the soils were oven-dry (n = 140). Hydrophobicity exhibited a parabolic relation to air-dry soil moisture (Figure

III.4). To describe the effects of soil drying on hydrophobicity three phases were distinguished. Phases I and II corresponded with the air drying phase and phase III to the oven-drying phase. Phase I covered saturated conditions until field capacity (w_{fc}). Soils did not present any water-repellent behaviour at this stage (Figure III.4). The second phase represented the moisture range between field capacity and air–dried conditions (w_{ad}, ca. 20%). During this phase, both t_i and $\alpha_{l\text{-}s}$ rose exponentially until a relative maximum (Figure III.4). Because the tests were applied after each 20% drop in gravimetric moisture content, the actual maxima of t_i and $\alpha_{l\text{-}s}$ were not necessarily included in the measurements. The dashed lines in Figure III.4 indicate the approximate positions of these maxima. Interestingly, the latter were generally fairly close to the permanent wilting point (w_{wp}). As such, the maximum levels of hydrophobicity occurred within the range of soil water available to plants. Pertinently, the slopes of the rising limbs of the lines linking t_i or $\alpha_{l\text{-}s}$ to w were much steeper than those of the falling limbs in most cases, which implies a slow recovery towards wetting ability. Also, the final values of t_i and $\alpha_{l\text{-}s}$ at the end of phase III never approached the initial values of the first, non-hydrophobic phase (Figure III.3).

Interestingly, the same pattern as described here, from phase I to III, was also observed in sandy Danish soils (De Jonge et al., 1999) for soil water contents below the air-dry state (i.e. 0-0.12 g/g). The observed variations in persistency and degree of water repellency after oven-drying were attributed to changes in the molecular configuration of the organic matter (i.e. changes in the orientation of so-called amphiphilic organic compounds) (De Jonge et al., 1999). When polar groups are exposed on the pore surfaces within the organic matter then soils are wettable (Ma'shum and Farmer, 1985) whereas exposing non-polar hydrophobic radicals to the exteriors of the soil particles makes the soil water repellent (Wallis et al., 1990). In the present study, the air-drying of the organic topsoils may have had a similar effect on the molecular configuration of the organic matter, producing the observed increase in water repellency. The fast decrease may be explained by the gradual reduction in the volume of organic particles and the formation of aggregates during drying allowing water drops to infiltrate.

III.3.4 WDPT and MED tests: effects of oven-drying

Soil hydrophobicity exhibited different patterns as a function of temperature during oven-drying of air-dry samples ($w_{ad} \approx 20\%$) (Phase III). Soils (n=140) were classified in four groups (A, B, C or D) depending on their hydrophobic behaviour (Figure III.4). In soils of type A oven drying caused an increase in both the time required for infiltration as well as in the contact angle. These effects were found for 56% of the soil samples. A similar result was obtained by Crockford and Richardson (2000) De Jonge et al. (1999) and Dekker et al. (1998), which might be caused by an increase in the alignment of the hydrophobic molecules (Doerr et al., 2000) and possibly by the migration of waxes contained in the organic matter to the particle surfaces (Franco et al., 1995). On the other hand, the opposite effect, a reduction in both t_i and $\alpha_{l\text{-}s}$, was observed on 11% of the samples, which were named type B. Decreases in time to infiltration and contact angle were also observed by Dekker (1998) for Dutch sandy soils. A third type exhibited differences in hydrophobic behaviour depending on the type of test applied. In these soils of type C the time to infiltration increased but the contact angle decreased. Type C soils represented 30% of the samples. Only 3% of the samples showed a decrease in the time to infiltration and an increase in contact angle (type D). Two of the 140 soil samples recovered their original water affinity after oven-drying but these were exceptions.

Such contrasting effects can not be explained by the amount of soil organic matter. Type A soils had a mean O.M. of 41 ± 13%, vs. soils of type B 34 ± 9%, type C 45 ± 11%, and type D 45 ± 14%. It is expected that part of the organic matter is volatilized at 105º C, therefore other components (e.g. the presence of amorphous materials; Wada, 1985) must be responsible for these variations in hydrophobicity.

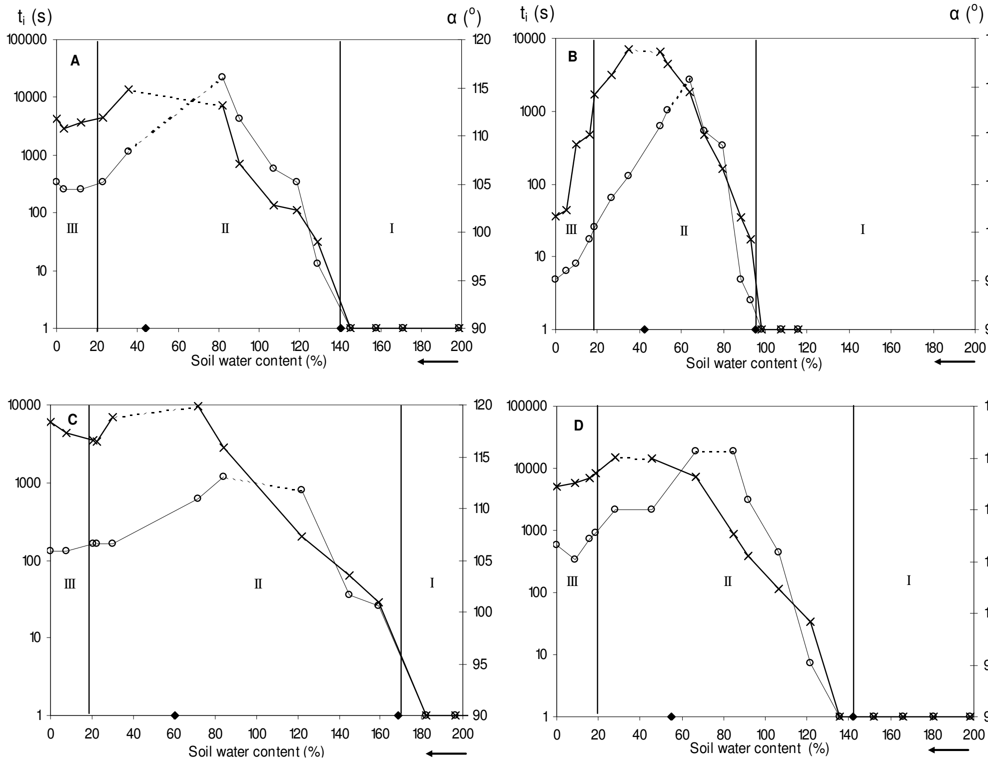


Figure III.4 Contrasting patterns in the time required for infiltration (left-hand abscise, crosses x) and contact angle (right-hand abscis, circles ○) as a function of gravimetric soil moisture content (%) in surface soil samples (0-0.03 m), Jelima catchment (La Gomera). Soil samples were subjected to air-drying from saturated conditions (phase I) to completely air-dry (20% soil moisture) (phase II) (note the direction of the arrow). Solid black dots mark field capacity (right) and wilting point (left) of the soil. Hydrophobic behaviour during oven-drying at 55°, 60° and 105° C corresponds with phase III. Types A, B, C, and D soils represent the four different types of hydrophobic behaviour observed during oven–drying (see text for explanation).

III.3.5 Proposed empirical models of repellency vs. moisture content: WDPT-*w* and MED-*w*

In order to reproduce the soil hydrophobic behaviour under naturally occurring drying conditions (phases I and II in Figure III.3), the time required for infiltration (t_i) and contact angle $\alpha_{l\text{-}s}$ were modelled as a function of gravimetric moisture content w during air-drying. In the case of the WDPT-*w* model, the following non-monotonic curve was fitted to 114 soil samples (r^2= 0.89):

$$t_i = (a + cw)/(1 + b\,w + d\,w^2) \qquad \text{III.3}$$

where t_i is time to infiltration (s), w is gravimetric moisture content (%), and a, b, and c are empirical constants. The average fitted curve and its shape parameters (see also below) are shown in Figure III.5.

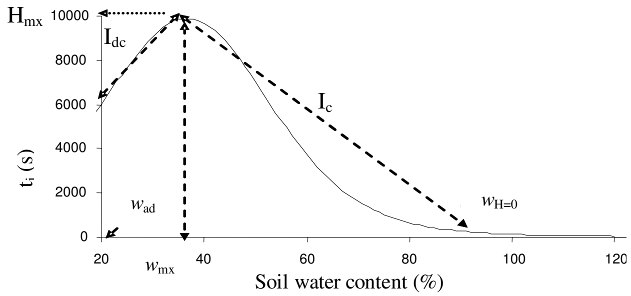


Figure III.5 Average curve relating time to infiltration t_i (s) to gravimetric soil moisture content (%) during air-drying. Curve shape parameters: mean maximum value of hydrophobicity (H_{max}), moisture content at maximum hydrophobicity (w_{max}), moisture content of air-dry soils (around 20 %) (w_{ad}), moisture threshold where soil starts to be hydrophobic (t_i=5 s) ($w_{H=0}$), mean slope increase index (I_c) and mean slope decrease index (I_{dc}).

To link $\alpha_{l\text{-}s}$ to w (MED-*w* model), the following non-monotonic regression was fitted to the results obtained for 123 soil samples (r^2= 0.90):

$$M_i = (e + gw)/(1 + fw + h\,w^2) \qquad \text{III.4}$$

where M_i is molarity of ethanol (mol/l), w is gravimetric soil moisture content (%), and *e, f, g, h* are empirical constants. Molarity of ethanol values were converted to contact angles (º) following the procedure of Roy and McGill (2002). The mean curve fitted to the MED data is shown in Figure III.6. The shape parameters defining the curve are the same as those used in the previous model.

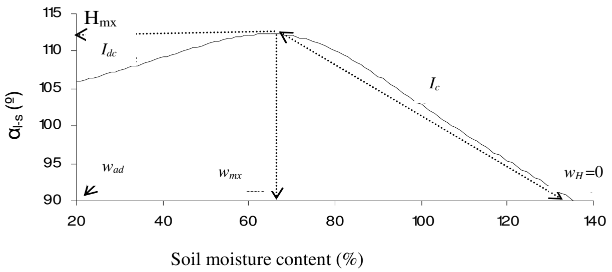


Figure III.6 Mean curve linking contact angle $\alpha_{l\text{-}s}$ (degrees) to gravimetric moisture content (%) during air-drying. Curve shape parameters: mean maximum value of hydrophobicity (H_{mx}), moisture content at maximum hydrophobicity (w_{mx}), moisture content of air-dry soil (around 20 %) (w_{ad}), moisture content where soil starts to be hydrophobic ($\alpha_{l\text{-}s}$=90°) ($w_{H=0}$), mean slope increase index (I_c) and mean slope decrease index (I_{dc}).

The models described above did not provide an adequate fit for 26 soil samples in the case of the WDPT-*w* model and for 17 samples in the case of the MED-*w* model. In most of these cases the pattern consisted of a monotonic increase in water repellence with no recovery of less hydrophobic conditions.

The average curves of Figures III.5 and III.6 may be used to assess how rapidly (I_c) the soils reach maximum hydrophobicity (H_{mx}) as well as their partial recovery during continued drying (I_{dc}). The moisture range between the start of hydrophobicity and the air-dry state ($w_{h0\text{-}ad}$) is a measure of the soil's susceptibility in that higher values of $w_{h0\text{-}ad}$ imply an earlier start of repellency. Comparison of Figure III.5 and III.6 shows that H_{mx} is reached much later in terms of time to infiltration (WTDP test) than in terms of droplet-soil contact angle (MED test). Conversely, upon further drying of the soils until they were fully air-dried, times to infiltration recovered more quickly (although soils did not become non-repellent again; Figure III.5).

To further explore the reasons for this behaviour, the various model parameters were regressed against soil organic matter content O.M. A modest positive correlation (r = 0.39) was found between O.M. and the integrated area under the curve (S) in the case of the WDPT method but not in the case of the MED method. De Jonge *et al.* (1999) obtained a good correlation (r = 0.79) between S and O.M. for mostly sandy soils in Denmark using the MED method. The present study found very slight positive correlations between O.M. and $\omega_{H=0}$ (r = 0.26) and H_{ad} (r = 0.07), and a negative correlation with I_{dc} (r =-0.07).

III.3.6 Variability in model predictions

Figure III.7 up and down show the empirical values of time to infiltration (n = 114 samples) and contact angle (n = 123 samples) for all the measured gravimetric moisture values, whereas the small panels in the main figures show the mean values of time to infiltration and contact angle for gravimetric moisture values of 20, 40, 60, 80, 120 and 140% using the two empirical models (i.e. Eqs. III.3 and III.4). Variability (standard deviation) increased with increasing times to infiltration (i.e. decreasing moisture content), as also observed previously by King (1981) and Jaramillo (2001) who attributed this to evaporation and soil hydraulic effects influencing the results during longer tests. However, variability in contact angle was increased at higher soil moisture levels (Figure III.7, lower panel). Therefore I_c is subject to higher variability than I_{dc} in both methods. From a methodological point of view, therefore, the MED test is to be recommended for use on dry soils and under conditions of extreme hydrophobicity (i.e. high values of α_{l-s}).

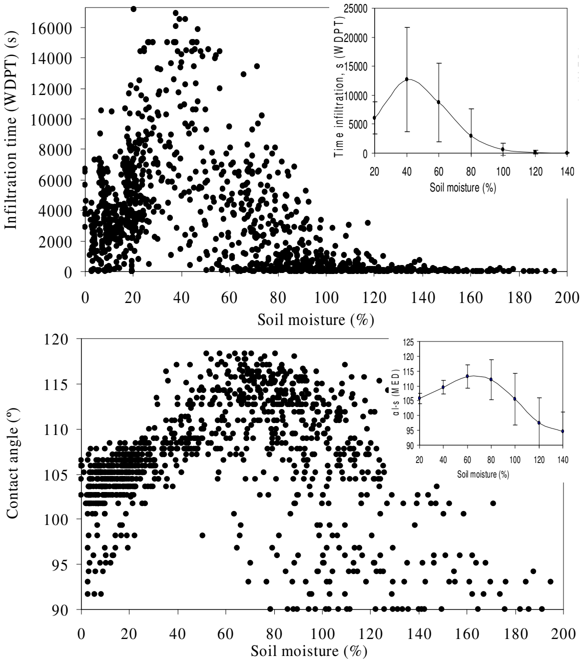


Figure III.7 Empirical (main figures) and modelled (small figures) changes in time to infiltration (upper panel) and contact angle (lower panel) as a function of gravimetric moisture content (%). Bars represent one standard deviation.

Regarding the methodology, applying two types of tests helped to better characterize soil water repellency. Values of t_i below 600 s as obtained with the WDPT test were linearly related to contact angles derived with the MED method, as also found by King (1981). Infiltration times above 600 s were not related to contact angle, possibly because when water droplets remain on the surface for such a long time, hydraulic conductivity and evaporation may influence soil water absorption. Such factors do not affect the results of the MED tests because the ethanol droplets remain on the soil surface for 10 s only.

III.3.7 Hydrological implications

Occurrence of soil water repellency in the study catchment was explored further using the WDPT-*w* model to predict the time to infiltration associated with four soil water conditions, 140% (near saturation), 120% (field capacity) and 20% (air-dry conditions). Results for 114 surface samples are shown in Figure III.8. As expected, non-repellent (i.e. t_i < 5 s; Table III.1) or slightly (moderate) repellent behaviour was dominant (78% of the samples) under wet conditions (140% moisture). A decrease in soil moisture to 120% (field capacity) caused a reduction in the number of non-repellent in favour of slightly and strongly water-repellent conditions up to 70%.

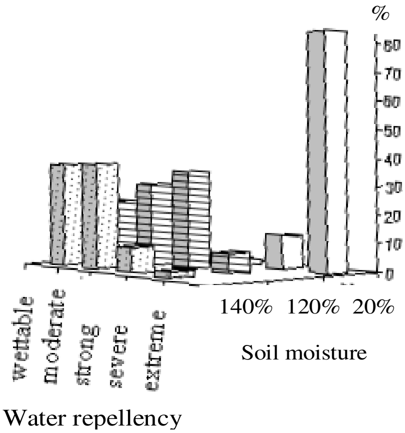


Figure III.8 Frequency of occurrence of different degrees of potential water repellency in soils with high organic matter content in the Jelima catchment for different gravimetric moisture contents as predicted by the WDPT-w model.

The presently obtained results suggest that the volcanic soils of the study area only exhibit full wettability when they are very wet, as was also found to be the case for dune sands by Ritsema and Dekker (1994). Such conditions are ensured only during periods of heavy rain (usually in autumn and winter in La Gomera; see Chapter IV). Periods with moderate or light rainfall during winter and spring may gradually cause soils to become less water repellent, but prolonged dry conditions (as frequently occurring in spring and summer) are likely to make them more water-repellent.

From the hydrological point of view, much of the first rains after the dry summer period are likely to run off or evaporate if the water is not able to infiltrate because of highly hydrophobic conditions (Bauters et al., 2000; Michel et al., 2001). Such conditions favour the occurrence of dry patches in soil profiles, with wet spots found only where the water was able to infiltrate (Figure III.9), as was also observed by Jaramillo et al. (2000). Prolonged rainy conditions seem to be required to 'break' surface crusting and restore soil wettability (DeBano, 2000; Leitch et al., 1983). However, no surface runoff was ever observed in the study plots even during heavy rain.

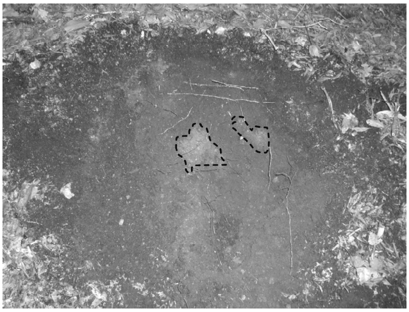


Figure III.9 Dry patches after heavy rainfall in a previously dried ridge top soil in the Jelima catchment, La Gomera.

III.4 CONCLUSIONS

Water-repellent conditions in the study catchment were found to be likely to occur down to a depth of 0.23 m. Soil water repellency as a function of decreasing moisture content was studied using a large number of samples in terms of the time required for applied water droplets to infiltrate and in terms of contact angle between droplets and sample surface. Hydrophobicity was found to be highly dependent on soil water content, and exhibited a non-monotonic pattern in which soils started to become water-repellent around field capacity (gravimetric moisture content w of ca. 120%) and reached maximum hydrophobicity around wilting point (w ~ 40%). The observed patterns were well reproduced by relatively simple equations. Soils with high pyrophosphate- to oxalate-extractable aluminium ratios (indicative of non-allophanic clay minerals) and high organic matter contents coincided with a high susceptibility to water repellency. However, organic matter content did not explain differences in degree and persistency of soil water repellence. Differences in the type of organic matter and other factors such as secondary organic compounds in vegetation and litter may affect water repellence of the surface soils but these aspects were not included in the present study.

Modelled frequencies of occurrence of various degrees of hydrophobicity suggested that effects of soil water repellency on rainfall infiltration are likely to be small under the wet conditions that tend to prevail in autumn and winter whereas strongly to extremely hydrophobic conditions are likely to occur over large parts of the study catchment during (prolonged) dry periods typically occurring in spring and summer.